C13.2:M56/9

GRI-84/0190

WORKSHOP ON FUNDAMENTAL RESEARCH ISSUES IN ORIFICE METERING

held at
National Bureau of Standards, Gaithersburg, Maryland
on
June 9-10, 1983

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Gaithersburg, Maryland 20899

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

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WORKSHOP SPONSORED BY:

The Gas Research Institute
in cooperation with
The National Bureau of Standards
and
The National Engineering Laboratory, United Kingdom
with assistance from
The National Science Foundation

FOR:

GAS RESEARCH INSTITUTE
Contract No. 5083-260-0838
GRI Project Manager
M. Klein
BASIC RESEARCH

September 1984

U. S. Depository Copy

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50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No.

4. Title and Subtitle
Workshop on Fundamental Research Issues in Orifice Metering

5. Report Date
September 1984

6.

7. Author(s)
G.E. Mattingly, E.A. Spencer, and M. Klein

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
National Bureau of Standards
Gaithersburg, Maryland 20899

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois 60631

National Engineering Laboratory
East Kilbride, Glasgow G75 0QU
Scotland, UK

13. Type of Report & Period Covered

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

An international workshop on orifice metering research is reported. This workshop, sponsored jointly by the Gas Research Institute, the National Engineering Laboratory in the United Kingdom, and the National Bureau of Standards (NBS) with assistance from the National Science Foundation, convened 100 attendees from 10 countries at NBS-Gaithersburg, MD on June 9-10, 1983. Attendees represented a broad range of interests and fluid measurements capabilites from theoretical and computational-numercial modelers and experimental fluid dynamicists to meter manufacturers and orifice users.

Attendees listed problem areas in orifice metering practice, discussed research projects to respond to these, and prioritized these efforts according to their perceived potential to improve orifice metering. Results indicate that there is widespread concern over a number of issues ranging from the practical aspects of making accurate differential pressure measurements in the field to the determination of orifice flow fields using laser Doppler velocimetry and computer techniques to the resolution of the different paper standards pertaining to orifice meters.

An extensive bibliography is included.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms
computer modeling; custody transfer; differential producers; fluid measurement; gas measurement; orifice experiments; orifice metering; process monitoring; research

c. COSATI Field/Group

18. Availability Statement:	19. Security Class (This Report)	21. No. of Pages
Unlimited		156
	20. Security Class (This Page)	22. Price

Title: Workshop on Fundamental Research Issues in Orifice Metering

Contractor: National Bureau of Standards, Gaithersburg, Maryland
GRI Contract Number

Principal Investigator: George E. Mattingly

Report Period: 2/1/83 - 10/31/83

Objective: To delineate, in terms of fundamental flow phenomena, the practical problems which stand in the way of improved accuracy in orifice metering; to establish the state-of-the-art in fundamental experimental and theoretical research in fluid flow and; to determine if that state-of-the-art can usefully be brought to bear on the solution of these practical problems in order to produce a major advance in metering accuracy.

Technical Perspective: It is estimated that one million orifice meters are currently being used for custody transfer, representing, thereby, a substantial capital investment. The state-of-the-art in orifice metering is based on an empirical approach developed over fifty years ago. Current standards of practice stem from measurements which were based on this empirical model and which were themselves made at least thirty years ago. A number of shortcomings in the model have been taken care of over the years through the introduction of over a dozen empirical correction factors of a strictly ad hoc nature. These correction factors, while once of sufficient accuracy for metering purposes,are too inaccurate at current gas prices. The development of a new model which includes each of the effects described by these factors at the accuracies now required must be based on an understanding of the interaction between the meter and the flow field. Results obtained from such studies could improve the accuracy of orifice metering through optimum redesign of pressure tap placements, the development of a new orifice equation, the development of a method for the averaging of pressure fluctuations, etc. Fundamental studies of sufficient detail have not been possible until quite recently because of the experimental and theoretical difficulties involved. The state-of-the-art in computer modeling of fluid flow and in fundamental fluid flow measurements has, however, now reached the stage where they can be used to understand fluid flow in orifice meters at a fundamental level.

Results: Attendees listed problem areas in orifice metering practice, discussed the design of research projects to respond to these, and set priorities for the problems and research projects. Widespread concern over a number of issues was indicated. Leading them are: (1) the need for improvement in pressure differential measurement, (2) the need to produce detailed measurements and characterizations of flow profiles as produced by specific upstream piping configurations and by the orifice

meter itself, (3) the need to develop a capability for the computer modeling of complex flow through various orifice geometries, (4) the need to carry out round robin tests among the many laboratories which generate orifice meter data, (5) the need to resolve differences in recommended meter installation design required by current national and international "paper standards."

Technical Approach: The accomplishment of the workshop's goal required close interaction between representatives of both the metering and research communities. Attendees were organized into four task groups with each attendee assigned to one such group. The task groups were assigned the following discussion topics: Group (I) the effects of the upstream flow profile and of the geometry of the orifice plate and the adjacent pipe; Group (II) the effect of the flow profile inside the meter itself and the influence of the piping configuration well upstream of the orifice plate; Group (III) practical aspects of orifice measurement; Group (IV) procedures for evaluating the accuracies of laboratory calibrations and facilities and of written specifications and standards, etc.

The three state-of-the-art presentations were first given to the entire workshop thereby establishing the current situations respectively in practical meter limitations, in the fundamental measurement science of fluid flow, and in the computer modeling of fluid flow.

The task groups met twice with reports presented to the entire workshop by the respective group chairmen after each meeting. The final recommendations of the four task groups were developed in ballot form by the organizers of the workshop and were presented to each attendee for ranking.

Project Implications: This workshop and report will be widely disseminated. The research community involved in fundamental research in fluid flow will thereby be made aware that an important industrial problem, that of improving the accuracy of large scale fluid flow metering, needs advances of a fundamental nature and that these advances can come from their efforts. At the same time, the practical metering community will be made to see that the problems currently standing in its way are fundamental in nature and that the current state-of-the-art in fundamental flow research can help solve these problems. Every effort will be made to ensure that the dialog between these groups, begun at this workshop, will continue so as to maintain strong interactions between these communities. The conclusions reached by the workshop have become part of the GRI program planning process and have led to a consistency between program plans of the basic and applied programs at GRI in the metering area.

WORKSHOP REPORT BY:

G. E. Mattingly
National Bureau of Standards
Gaithersburg, MD

E. A. Spencer, OBE
National Engineering Laboratory
East Kilbride, Scotland, U.K.

and

Max Klein
Gas Research Institute
Chicago, IL

PREFACE

There is an urgent driving force behind the need for improved accuracy in fluid metering. Recent rapid escalation in the value of the fluids being metered, such as natural gas and oil (but not exclusively these), has put a very high value on metering accuracy. Improved metering performance is also needed in the chemical process industries where optimal control on continuous processes is critical to productivity. The need for greater accuracy must be placed in a context which includes the fact that recent years have seen extensive advances in just the kind of fundamental fluid flow research which might be used to satisfy this need for greater accuracy. Advances have resulted in an ability for doing computer modeling of increasingly complex flow fields to improving accuracy. Other advances, like the use of lasers, have produced an ability to investigate complex flow fields in the laboratory.

The organizers hope that this workshop can distinguish those problems limiting accuracy at the state-of-the-art in the practice of metering which are being hindered by lack of fundamental knowledge. They further hope that the workshop will describe the potential for fundamental flow research to contribute to the solution of such problems. The organizers of this workshop indeed felt that the time was propitious for a serious discussion of the potential for using these research advances for a general move forward of the state-of-the-art of fluid metering technology.

The organizers felt that the academic community was not aware of the pressing problems of fluid metering technology. It was felt that, on becoming aware of this urgent practical need, academics might, where possible, include in their research problems, flow situations directly appropriate to fluid metering problems. This can often be done without sacrifice of basic research goals.

The organizers further felt that the engineering community was not aware of the new fundamental research tools now available and their potential for providing solutions to practical engineering problems. Such awareness could result in stronger financial and moral support of the academic community and could cause the metering community to make adjustments in planning to include the potential of fundamental flow research.

This workshop was built around the orifice meter since, at least in the United States, that meter is so widely used in most applications that capital investment in such meters is enormous. It is, in fact, estimated that on the order of one million such meters are actively involved in custody transfer in the United States. One company alone claims to have 19,000 such meters in place! The conversion to other meters is therefore extraordinarily expensive and obviously should not be undertaken until the limitations of the orifice meter are understood at the most fundamental level.

It is to be hoped that this workshop will be just the first of several with the subsequent ones convened to address the problems at the state-of-the-art in other fluid metering technologies as well as to discuss the development of new metering technologies based on new insights emanating from fundamental fluid flow research.

DEDICATION

to

Professor S. R. Beitler
Department of Mechanical Engineering
Ohio State University
Columbus, OH

"It is very right and appropriate that special reference be made here to a very special person who is one of the attendees at this workshop.

It is given to very few people to become legends in their lifetimes. It is also rare for generations of instrument engineers to have the opportunity of meeting and being influenced by a person whose work has become established as a cornerstone in the development of their particular art or science. We at this workshop are fortunate to have with us such a person.

Professor S. R. Beitler, Sam to thousands, undertook a task in orifice metering more than 50 years ago. He carried out that task in a way which was ahead of the established standards of measurement at that time. It is hard to believe that this was as far back as the 1930's. Indeed, his work has remained an inspiration and an achievement as valuable today as at any time in the past five decades. This is because, in carrying out that task, Sam Beitler characteristically showed both a care for his work and attention to pertinent details. He has continued to show this approach subsequently in many ways in his leadership of programs on research and standardization, not only in flow measurement but in the formulation of steam tables and in other projects. Furthermore, and this should be a lesson to all, Sam Beitler took the trouble to record his data accurately and then to write up his work in published reports. In consequence, we, of subsequent generations throughout the world, can even now turn back to these reports for guidance.

We record our pleasure at his presence here at this workshop at the National Bureau of Standards in Gaithersburg and our appreciation for his many achievements especially in the areas with which we are concerned here. We also record our happiness and gratitude to his wife Katherine for her support and encouragement of him and us.

It is indeed with great pleasure that we dedicate this workshop report to Sam Beitler."

.....By Dr. E. A. Spencer, O. B. E.
June 21, 1983

Katherine L. Butler

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ACKNOWLEDGEMENTS

Contributions to this workshop and to this report have been made by several persons and organizations. Significant among these are those made by Dr. George K. Lea of the National Science Foundation. His inputs regarding topics, participants and format are cited specifically. In addition, his efforts toward securing the sponsorship to ensure the attendance of the academic participants are gratefully appreciated.

National Bureau of Standards (NBS) personnel whose involvment went well beyond the expected and who therefore merit specific note are: Polly H. Gurewitz, Susan L. Johnson, Carol A. Thomas, Sara R. Torrence, Kathleen D. Kilmer, Lawrence N. Hale, G. James Sonnichsen, and H. Mark Helfer. Dolores Moreno of The Gas Research Institute (GRI) contributed most commendably both to the workshop itself and in the preparation of the preliminary materials and of this report.

EXECUTIVE SUMMARY

INTERNATIONAL WORKSHOP ON ORIFICE METERING RESEARCH

An international workshop on orifice metering research was convened at NBS-Gaithersburg on June 9-10, 1983 to discuss measurement problems confronting orifice meter users and to develop ways to reduce the current levels of uncertainty associated with such meters. Orifice meters are the most widely used devices for the custody transfer of natural gas and of petroleum and petrochemicals. Such meters are also the devices most frequently used for the control of the rate of fluid flow in the process measurement and control industries.

With prices of fluid resources increasing very rapidly, there is a growing concern among buyers and sellers alike for improved orifice metering accuracy and repeatability. Recent advances in fundamental measurement techniques and in the computer modeling of complex fluid flows in various geometries offer new opportunities to achieve increased accuracy in orifice metering. The purposes of this workshop were to examine the needs perceived by the engineering community for improvement in orifice metering practice and to describe how to satisfy such needs using new experimental and modeling methods.

Sponsored jointly by the Gas Research Institute, the NBS, and the National Engineering Laboratory in the United Kingdom, with assistance from the National Science Foundation, the workshop brought together 100 attendees from ten countries. The capabilities of those in attendance spanned a broad range of fluid measurement practices. Present were theoretical and computational numerical modelers, experimental fluid dynamicists, meter manufacturers, and orifice users from various industries.

Attendees listed problem areas in orifice metering practice, discussed the possible designs of research projects which might respond to these, and prioritized these efforts according to their perceived potential for improvements in orifice metering practice. Results indicate that there is widespread concern over a number of issues. Leading this list are:

- the need for improvement in the performance of the pressure differential measurement instrumentation and the need to understand the complex nature of the pressure fields detected by these devices,

- the need to produce detailed measurements and characterizations of flow profiles as produced by specific upstream piping configurations and by the orifice meter itself. This might require using combined computational and experimental techniques (i.e., laser Doppler velocimetry (LDV), anemometry, and high speed flow visualization methods). These data were considered essential to the understanding of the salient phenomena that control orifice performance,

- the need to develop a capability for the computer modeling of complex flow through various orifice geometries and the need to determine the potential for using such modeling to elicit the qualitative dependences of various parameters on the relationship between the actual and indicated flow rates as obtained using orifice meters.

- the need to design and carry out careful round robin testing of the measurement capabilities of the many laboratories which generate such orifice meter data as are used to formulate empirical performance equations,

- the need to bring about a resolution of differences in recommended meter installation requirements given in current national and international "paper standards."

Attendees toured the NBS fluid metering research and calibration facilities and discussed recent and current fluid dynamic projects in orifice flows and related topics. Particular interest was shown in the NBS projects which were designed to characterize sources of pressure fluctuations that are created in fluid jets. The characterization is based on the use of such techniques as numerical modeling and special experimental techniques (LDV, anemometry, and high-speed flow visualization).

The success of this workshop was emphasized when, in the concluding session, attendees urged that workshops similar to this one be convened in the future both to review research progress aimed at improving orifice metering and to discuss methods for improving other fluid metering methods. Such workshops would have as goals the reduction of fluid measurement uncertainties to satisfactory levels and the maintenance of the interactions between the basic research and metering communities established in the current workshop.

WELCOMING REMARKS

Mr. Samuel Kramer
Acting Director
National Engineering Laboratory
National Bureau of Standards
Washington, D.C. 20234

"The NBS established a role for itself in developing orifice technology in the early 1920's. NBS staff members Mr. Howard S. Bean and Dr. Edgar Buckingham, together with others, and especially in collaboration with Professor Samuel R. Beitler of Ohio State (who is present here today), actively conducted, supervised and/or consulted on orifice testing programs over the three decades from the 1920's until the 1950's. The results of this combination of testing programs, with others in the United States and abroad, have produced the state-of-the-art in orifice metering as we know it even today in the 1980's.

Because of dramatic increases in gas prices in recent years, it has now become necessary to re-examine the uncertainty levels of orifice metering associated with the state-of-the-art as defined by this earlier work. To accomplish this, testing programs are in progress at NBS-Boulder under the sponsorship of GRI, and at NBS-Gaithersburg under the sponsorship of the American Petroleum Institute (API). Similar programs are simultaneously underway in Europe. It is now beginning to be recognized that, in addition to empirical testing methods, other research tools, and especially newly developed laser measurement and computer modeling techniques, are already available for understanding orifice flows at a fundamental scientific level.

It is the purpose of this workshop to discuss fundamental issues that affect orifice performance, to suggest fundamental research programs and to attempt to set research priorities. The task of the attendees seems clear, at least in principle; it is certainly most timely and appropriate; and I wish you every success in carrying out the goals of this workshop - I shall look forward to hearing of your results."

NBS-GRI WORKSHOP ON FUNDAMENTAL RESEARCH ISSUES IN ORIFICE METERING
JUNE 9-10, 1983
NBS-GAITHERSBURG, MARYLAND

Day 1

8:10 AM	NBS GREEN AUDITORIUM AREA Attendee Packet Pickup
8:30 AM	NBS GREEN AUDITORIUM (Chairman: M. Klein) Opening Remarks - Mr. S. Kramer, Acting Director National Engineering Laboratory, NBS
8:45 AM	Overview 1: Orifice Metering - State-of-the-Art. (R. W. Miller - Foxboro Company)
10:00 AM	Overview 2: Fundamental Flow Research - Potential for Contributing to Orifice Meter Technology. (G. E. Mattingly - NBS)
11:00 AM	Overview 3: Potential Role of Computer Modeling in Orifice Research (Professor K. N. Ghia - University of Cincinnati).
12:00 Noon	NBS GREEN AUDITORIUM Task Group Formation
12:45 PM	Lunch - NBS CAFETERIA
2:00 PM	NBS LECTURE ROOMS: Task Group Sessions
4:15 PM	NBS Building 230 - Lab Tours (Chairman: G. Mattingly)
5:30 PM	NBS EMPLOYEES LOUNGE Reception
6:00 PM	NBS SENIOR LUNCH CLUB Buffet Dinner Speaker - Mr. Lee Wallace, Counsel Regulatory and Legislative Analysis GRI - Washington Office

Day 2

8:30 AM — NBS GREEN AUDITORIUM
(Co-Chairmen: M. Klein and G. Mattingly)
Task Group Chairmen present summaries of their group's product to all attendees. Discussion period after each to provide opportunities for "cross-fertilization" between task groups. Each group is allotted 45 minutes.

11:30 AM — NBS LECTURE ROOMS
Task Group Sessions to incorporate results of morning "cross-fertilization"

12:45 PM — Lunch - NBS CAFETERIA

1:35 PM — GROUP PHOTO

1:45 PM — Brief Presentations on Current Orifice Testing Programs:
a) Gas Orifice Meter Testing at NBS-Boulder - J. A. Brennan
b) The EEC Orifice Coefficient Program - E. A. Spencer
c) NBS-NEL Orifice Cross-Check Testing Program - G. E. Mattingly
d) Orifice Meter Testing in Water at NBS-Gaithersburg - J. R. Whetstone

2:45 PM — NBS GREEN AUDITORIUM
Final Session
(Chairman: E. A. Spencer)
Open Discussion. Grand Ballot

4:00 PM — Adjourn

INTRODUCTION

Max Klein
Gas Research Institute
Chicago, Illinois

This workshop was put together by its organizers on the basis of their intuitive feelings that the state-of-the-art in orifice meter practice, as defined in the 1930's by Beitler at Ohio State and Bean and Buckingham at the National Bureau of Standards (NBS), may have actually created the limits of attainable accuracy for orifice measurements based on the equations both then and now in use. This implies, in essence, that inlet flow conditions, the combination of the orifice plate and its geometry, the location of the pressure taps, the measurement averaging techniques for differential pressure, the orifice equations used, etc. cannot, within current practice, be improved to reach a level of accuracy beyond that currently attainable under controlled laboratory conditions. These intuitive feelings, if indeed valid, could have led to a workshop which was simply an exercise in "hand wringing". It was our feeling, however, that, before it can be said that it is possible or impossible to make any major improvement in accuracy, an understanding has to be established of how each of the factors involved contributes to limiting the accuracy attainable with the orifice meter. This might be done by means of an empirical testing program in which each parameter is varied. Because of the large number of parameters involved and because of the potential for their non-separability resulting from their interaction with each other through the fluid medium, this approach would require an extraordinarily large testing program. Such a program would take many years and considerable resources and would probably produce results which, because of the large number of combinations of parameters, might be hard to summarize.

A more realistic approach might involve the development of a fundamental approach out of which could come a theoretical model whose study by analytical or numerical means could yield the contribution of each effect to the fundamental structure of the flow and hence its contribution to the limitations in attainable metering accuracy. In fact, the organizers felt that the current state-of-the-art in computer modeling of flow processes and in fundamental measurements for characterizing flow phenomena might indeed, for the first time, allow for the possibility of designing research programs to produce a basic understanding of the flow process in the specific geometry of an orifice meter.

In order to explore the possibilities associated with this situation we have aimed to bring together experts in all the empirical aspects of orifice metering and researchers who have been involved with internal fluid flow phenomena. In particular, we hope here to delineate the metering problems, to describe the current capabilities of fundamental research in flow phenomena and to determine if the latter might be used to solve the former. This introduction is meant to expand on the intuitive feelings stated above, albeit in a limited way; to describe the structure of the workshop and to introduce the overview papers and task groups.

Huge sums of money are involved in the commerce associated with natural gas. In the United States alone some 17 trillion cubic feet (tcf) of gas are consumed annually with a value which is on the order of 50 billion dollars. If it is assumed that this gas changes ownership only three times on the average during its flow from the wellhead to the burner tip, the total financial exchange involved (and hence the total value associated with the metering of this commodity) reaches 150 billion dollars per year! Clearly, then, any research which produces even the slightest improvement in the overall accuracy of the metering process can hardly help but be cost effective.

The net visible operating cost to the national commerce in natural gas of error in the metering process is not simply computed by applying an average percentage metering error to the total value of that commerce and defining the result as the national cost of error. Account must somehow be taken of the averaging out of positive and negative random errors. Although an exact calculation is not possible without specific knowledge of the character of the errors involved, reasonable estimates can be made based on reasonable assumptions. Consider the following calculation, for example. Under optimum laboratory conditions, any measurement has an associated uncertainty which can be observed both as data scatter and as data offset between laboratories. As regards metering, even under the best of laboratory conditions, scatter in orifice meter readings, for a particular laboratory as well as among different laboratories, is no better than 0.5%. (There have been instances where agreement among laboratories appears to approach 0.3% but the question of the degree of laboratory independence in such comparisons, i.e. the question of common systematic errors, suggests that a slightly larger value of 0.5% might be better used.) In its typical operations, a calibration facility, such as that of the National Bureau of Standards, finds that the degradation in the measurement of any given quantity between that obtained under the best laboratory conditions and that obtained in the field is generally an order of magnitude. This means that, based on the above numbers, errors in orifice metering in the field might be expected to approach 3 to 5% or ten times that observed under controlled laboratory conditions. The general concensus, in fact, appears to be that orifice metering in the field has an accuracy which is somewhere between 0.5 and 3%. For our purposes, a conservative estimate for this error (i.e., one on the low side) might be taken to be 1.5%. Assuming then that gas is metered in the field three times on its way from the wellhead to the burner tip (which is also an underestimate) means that one can expect errors in metering the 17 tcf of gas consumed annually in the United States, if summed in absolute value, to be roughly three times 1.5% of 17 trillion cubic feet (i.e. 17 billion mcf) or 750 million mcf per year. Assuming, then, an average price for this gas of $3.00 per mcf, this error has a total value of 2.25 billion dollars per year! But, since this estimated total error is composed of random and systematic components, a sum over absolute values would not be legitimate. Maintaining our conservative approach of underestimating all errors, let us assume that only 10% of this error is not random. It follows then that a conservative estimate of the net national value of uncancelled systematic error in metering comes to 225 million dollars per year. This is roughly two thirds of a million dollars per day. Since this error is systematic, there is no guarantee that it is distributed among the various parties to custody transfer contracts in an equitable fashion.

There is another way of estimating this quantity. A look at Gas Facts, a publication of the American Gas Association (AGA), shows the average unaccounted-for gas in the U.S. to be approximately 2.5% annually. Unaccounted-for gas has a number of sources. For purposes of this rough calculation, let us assume that these sources are mainly four, namely an error due to not correcting for temperature and pressure at the end user's meter, an error due to gas theft, one due to gas leakage, and metering error. The first of these has been estimated as accounting for perhaps half of the unaccounted-for gas. Let us assume further that each of the other three represent equal amounts of gas so that each contributes roughly 0.5% of the total annual commerce in natural gas. The estimated value of the unaccounted-for gas due to metering error is then seen to have an annual value on the order of 250 million dollars per year, or, again, roughly two thirds of a million dollars per day as averaged over the entire year.

The latter method of calculation deals with a net effect (i.e. the net national total of unaccounted-for gas as published by AGA) and hence is related to uncompensated error in the system. It is, therefore, a measure of the systematic error. Random errors presumably have cancelled in the various metering processes that took place. It should be remembered that these figures are mainly reported to AGA by distribution companies. Such companies tend to meter gas they buy with orifice plate meters and to meter gas they sell with positive displacement meters. Each of these operates on quite a different principle and hence their systematic errors might tend not to cancel.

Another aspect of the economic value associated with improving orifice meter performance has to do with the size of the capital investment in those meters already in place. It has been estimated* that there are approximately one million orifice meters in current use in the United States. Replacement of each meter by a meter based on a different measuring principle must cost well in excess of $10,000. If that is taken as a conservative estimate of replacement cost, then, replacement of all meters in current use would require ten billion dollars. (Perhaps a better use of these numbers would be to state the cost of total replacement as ten billion dollars for each unit of $10,000 in individual cost). Assuming the modification of current meters based on new knowledge for improving their performance to be cheaper than replacement allows for the introduction of yet another dollar value for research results. Thus, even if modification of the meters were as much as half the cost of their replacement, a saving of five billion dollars (for every ten thousand dollars of average replacement value) would result.

Clearly, any research aimed at improving the accuracy of orifice meters must be cost effective since any research program so mounted would involve but a small fraction of the cost of metering error and of the difference in cost

*Private communication from several metering engineers. The reasonableness of this estimate is based on the fact that another metering engineer informed me that his company itself has close to 20,000 meters in place.

between meter modification and replacement. We have already indicated that an empirical testing program cannot be the sole approach to studying this problem because of the enormity of the related task. A more fundamental approach based on flow models might have the advantage of requiring much less data for use in determining the parameters in such models, hence it might involve much less in the way of research resources. Until quite recently, however, there was little potential for such fundamental research in fluid flow to contribute to improving the accuracy of orifice meter practice. The research tools were not available. Thus, until recently, computational methodology could only produce very approximate calculations for modeling flow problems. The models involved only remotely approached anything related to the flow of gas through even as simple a geometry as that of the orifice plate. Predictions made on the basis of such computations could not then be related to actual practice with any degree of confidence. Furthermore, the state-of-the-art in fundamental experimental measurements of fluid flow through orifice plate geometries was relatively primitive. Results of such measurements were hard to relate to what takes place in an actual meter in the field. The relationship between experience in the field and the results of computation and of fundamental experiment, in fact, rapidly became clouded as accuracies of interest were reduced below several percent. In other words, the potential for improving orifice plate accuracy other than by empirical testing methods was, until recently, severely limited.

There appears to have been a common consensus, however, that an improved empirical testing program, using modern techniques of measurement and more extensive measurements might indeed improve on the accuracy of the original Ohio State measurements. Such an approach was thought to be capable of improving the accuracy of the orifice plate discharge coefficient and hence of metering practices. Preliminary results from the calibration-testing programs currently underway at NBS Boulder and NBS Gaithersburg indicate that things are not so easy and that a simple, straightforward modernization of the earlier work without detailed study of the flow process will probably only produce approximately the same level of accuracy as obtained at Ohio State albeit under better controlled experimental conditions.

The potential for fundamental improvement in the metering equations has recently changed, and is, in fact, undergoing continuing and rapid change. The advent of improved computing technology, numerical methods, and computer models for complicated flow systems, now make it feasible to produce meaningful predictions of flow in geometries such as those of the orifice meter based on computational modeling. The advent of the laser and the subsequent development of the laser Doppler velocimetry now make it possible to carry out experimental measurements of a fundamental nature on fluid flow through orifice geometries. This could indeed lead to a fundamental modification in orifice flow theory and hence in metering practices.

It is the purpose of this workshop to bring together metering engineers and basic research people, the latter mostly from the academic community, to discuss this potential. Our purpose in so doing is to place before the academic community the engineering characteristics of the orifice metering

problem in terms which can be translated into the language of fundamental fluid flow phenomena and techniques. In addition, we wish to place before the measurement engineer, the state-of-the-art and current potential associated with fundamental research in both modeling and experiment in terms which relate to the problems of that orifice metering engineer. This latter presentation must allow the orifice metering engineer to see the potential of fundamental research for solving his orifice measurement problem.

The problem which our workshop is to address might be summed up, therefore, as follows. The accuracy of orifice plate measurements in the field is currently assessed at perhaps 1.5%. On the other hand, under the best laboratory conditions, such measurements can be made probably no better than 0.5%. This appears to be reinforced by recent tests at NBS and elsewhere using modern measurement and data analysis techniques. One cannot expect to improve on a factor of three between laboratory and field accuracies. This, therefore, leaves little hope for the improvement of accuracies in the field until laboratory accuracies themselves have been improved. This indicates further that purely empirical methods will probably not produce better results than have been available for the last several decades. Meanwhile, the state-of-the-art in computer modeling and in fundamental fluid flow measurements has reached a stage where it becomes possible for predictions of the macroscopic fluid flow quantities measured in a metering installation to be made from detailed knowledge of the flow field on a microscopic level. This could lead to improved accuracy through optimum redesign of pressure tap placements, the development of a new orifice equation, perhaps the development of a correct method for the averaging of pressure fluctuations, etc. The purpose of this workshop, in short, is to bring to bear, through application of the state-of-the-art in fundamental fluid flow research, a range of perspectives on the problems involved in improving the accuracy of orifice meter measurements. Our efforts should attempt to determine if this state-of-the-art is indeed ready and able to contribute to this substantial national industrial problem.

ORIFICE METERING - STATE-OF-THE-ART

by

R. W. Miller
The Foxboro Company
Foxboro, MA

Introduction

Though most people consider the history of orifice flowmetering as beginning with its commercial development in the 1900's, especially for use in the measurement of natural gas at the turn of the century, its origins reach back into Roman times. The aqueduct built by the Romans supplied water which was "metered" by an orifice into the household, the buyer agreeing to pay his water bill by the size of the orifice bore.

In modern history the orifice gained an importance in flow metering which it reluctantly relinquishes. This is attributable to the simplicity of its construction, low cost, reliability, user familiarity, and its apparent ruggedness at the accuracy levels which were, until recently, quite adequate. National and international standards have been written around such meters. These various standards have been based on different sets of research results and, in many instances, on different methods of plate manufacture and of the attached pipe, (each with its own limitations) and on different pressure tap locations. It was inevitable that there should be differences among them, particularly since standards are written by "committee" and no two committees interpret data in exactly the same way.

It is understandable that the engineer who is working in the refinery or at a measurement site is not aware of the differences between standards and that he believes in the absolute accuracy of the published standard which he happens to be using. In the future, it would be helpful if those involved in the writing and production of such standards (API, AGA, ASME, ISO, IEC, OIML, SAMA and so on) were careful that their standards are compatible so that those working from standards of apparently different origin produce measurements which produces the same calculated flow rate.

This paper will attempt to identify some of the problems which exist in current orifice metering practice as well as to describe some of the differences among the current standards.

Orifice discharge coefficient and gas expansion factor

The discharge coefficient and gas expansion factor for an orifice meter are entirely empirical quantities. Equations for the discharge coefficient and the gas expansion factor which have been adopted by standards writing committees have depended on the particular test data available to those committees. ANSI 2530 (1978) proposes the AGA-3 (1955) equation, whereas ISO 5167 (1978) proposes the Stolz (1977) formulation for the prediction of the discharge coefficient. On the other hand, ANSI 2530 and ISO 5167 both propose the Buckingham (1932) equation for the expansion factor. Furthermore, being entirely empirical, these quantities can only be described in terms of equations based on engineering judgment and a selected mathematical form. This makes interrelation approximate and extrapolation outside of the data range highly suspect.

As an example, consider the (Buckingham, 1932, von Guy Thibessard, 1960, Head, 1973) equations which have been proposed for the gas expansion factor, Y, (Figure 1).

ISO/ASME/ANSI2530 $$Y_1 = 1 - (0.41 + 0.35\beta^4)\frac{x_1}{k}$$

von Guy Thibessard $$Y_1 = 1 - [0{,}3707 + 0{,}3184\,\beta^4]\left[1 - \left(\frac{p_2}{p_1}\right)^{1/\kappa}\right]^{0{,}035}$$

HEAD $$Y_1 = 1 + s_1(1 - \epsilon)/\gamma$$

$$s_1 = -0.258 - 1.324\,(C_{ci} - 0.5)$$

$$C_{ci} = 0.6 + 0.29\beta^4$$

$$x_1 = \frac{p_n - p_p}{p_n} = \frac{\Delta p^*}{p^*_{f1}} = \frac{h_w}{27.73 p_n}$$

$$\frac{p_p}{p_n} = \frac{p^*_{f2}}{p^*_{f1}} = 1 - x_1$$

FIGURE 1

Although differences among these are relatively small in absolute value, (0.2%), it is important to note that the percent uncertainties attached to the values calculated using these equations can be quite significant, particularly at low operating pressures. For example, if the calculated gas expansion factor is 0.98, it can only be stated with a 95 percent confidence level that the true value lies between 0.978 and 0.982. Improvement in the prediction can only be achieved by a better thermodynamic understanding of the radial and axial expansion mechanism after the streamlines exit from the plate, and by verifying these results with more accurate tests.

The discharge coefficient for all differential pressure producers is initially obtained by calibration with a liquid, usually water. These data are then used to establish a predictive equation. It is interesting to contrast the behavior of the orifice discharge coefficient with that obtained with other meters (Miller, 1983, Figure 2). While the discharge coefficients for venturi meters and nozzles are essentially constant in the turbulent flow regime and characterized by a decline in the laminar region, the orifice plate coefficient exhibits a significant peak at the lower Reynolds numbers. As shown in Figure 2, the orifice discharge coefficient, though virtually constant over the turbulent flow regime at high Reynolds numbers, increases with decreasing Reynolds number and only starts falling again after the laminar region is reached.

Being also totally empirical, the discharge coefficient has interpolation and extrapolation problems similar to those for the expansion factor. Equations were developed for fitting the available test data, which had been taken over a very narrow range of the Reynolds number. These fits were first done by individuals in the firms manufacturing and selling orifice meter runs, then by research workers and finally by those responsible to standards committees trying to rationalize the different equations developed from essentially the same data base. Thus, for example, the Buckingham equation, (AGA-3, 1955) developed in the early 1930's from the Ohio State University (OSU) experimental data was adopted in the USA and is still given in the AGA-natural gas measurement standard. The Stolz equation (Stolz, 1977) was developed during the last decade. Its purpose was to make the tables in the European national standards and in the earlier ISO Recommendation R541, (1967), consistent with the OSU data (Beitler, 1967). This more rational equation is simpler and easier to implement than the Buckingham equation. Additionally, it represents all tapping arrangements and replaces the three equations presented in the older standards.

The experimental data on which these equations were based scatter within a band (two sigma) of $\pm$1.3 percent around the values calculated from the equation. These data have been analyzed on different occasions by different people (Dowdell, 1970, Miller, 1974, 1979) with different conclusions reached. For example, in 1960, the ASME Fluid Meters Committee concluded that the sixth edition of their report should state that the Buckingham equation had an uncertainty of $\pm$ 1 percent rather than the $\pm$ 0.5 percent previously

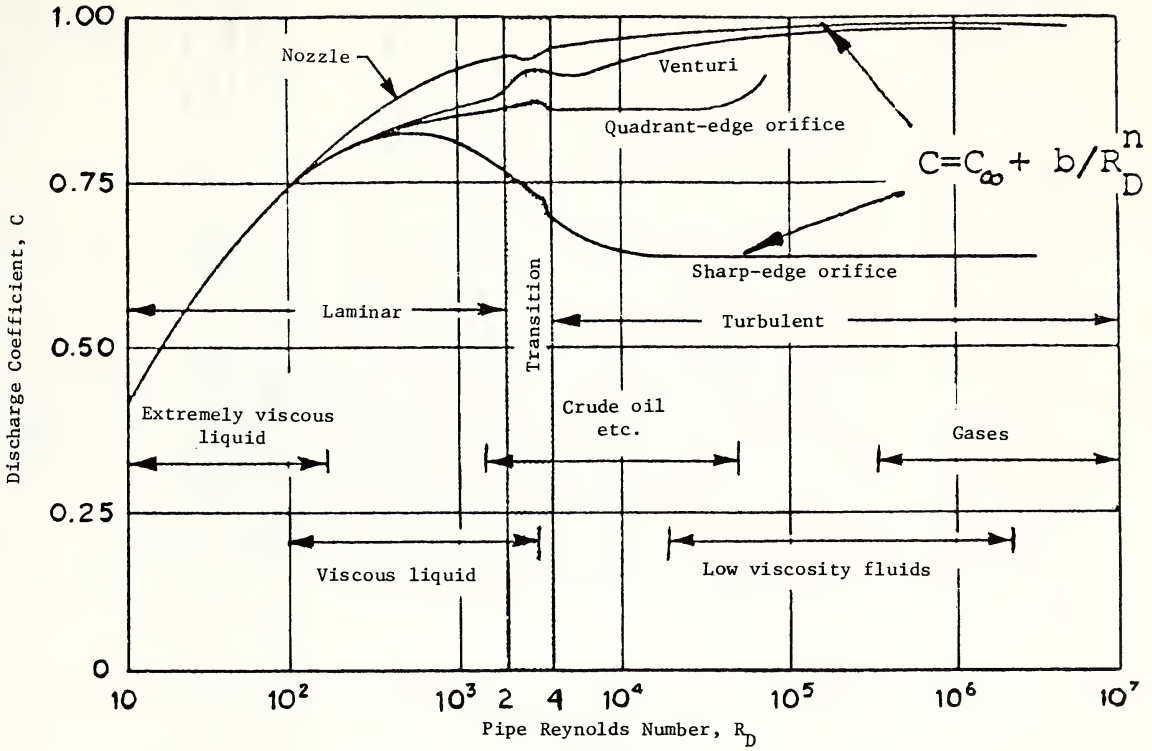

1.00
0.75
0.50
0.25
0
Discharge Coefficient, C
Nozzle
Venturi
Quadrant-edge orifice
$C=C_\infty + b/R_D^n$
Sharp-edge orifice
Laminar
Transition
Turbulent
Extremely viscous liquid
Crude oil etc.
Gases
Viscous liquid
Low viscosity fluids
10
10^2
10^3
2
4
10^4
10^5
10^6
10^7
Pipe Reynolds Number, R_D

FIGURE 2

ascribed to it by the AGA Report and prior editions of Fluid Meters (1971). In 1981, Fluid Meter (ASME 1981) recommended the Stolz equation be used for all tappings in later editions. The ISO Recommendation R541 (1967), on the other hand, had an uncertainty statement of $\pm$ 0.6 percent, later rising to $\pm$ 0.9 percent for the same equation. For beta values up to 0.6, the Stolz equation (1977) given in ISO 5167, (1978) has a "committee" assigned uncertainty of $\pm$0.6%. For higher beta values, the assigned uncertainty is taken equal to beta.

These claims must be treated with caution since, in many instances, the actual test data used in developing the equation were selected subsets of the OSU (1935) data. By this is meant that the data base was "cleansed" by the analysts, each proceeding in his own way. Thus, the Stolz analysis used only 303 results out of the original 1000 OSU test points. The remainder were eliminated for a number of different reasons which have never been fully explained in the literature. While the justifications used for the elimination of these data might be reasonable to some, it is important to consider the possibility that the results obtained by the normal user might also contain some of the same factors associated with the deleted data. This could mean that a user's actual meter run and installation might not conform to the physical situation associated with the tight selection of "good" data. Fig. 3 is a plot of the entire set of OSU data (1935) over the range of Reynolds numbers tested presented as a scatter about the values from the equation calculated (AGA-3, 1955).

There are now more recent data apart from the OSU data. It is important to consider all data as the need increases for developing standards for situations at and beyond the limits of the size range, diameter ratios and the Reynolds numbers associated with the OSU data, and to determine within these ranges how other data are represented by the equation. The OSU experiments (1935) did not include pipes larger than 14 inches in diameter whereas much natural gas is now being carried in high pressure pipelines of 20, 24, 32 inch diameter and even larger.

Daniel Industries and the Foxboro Company have each obtained test data for pipes with diameters from 2 inch to 24 inch. These were not included in the development of either the Buckingham or Stolz equations. Also, the Foxboro Company completed tests using oil which went down to pipe Reynolds numbers of 2000. The Foxboro oil data (Miller, 1979) are contained in Figures 4 and 5 for two beta ratios and show clearly that prediction at the lower Reynolds numbers is not particularly good.

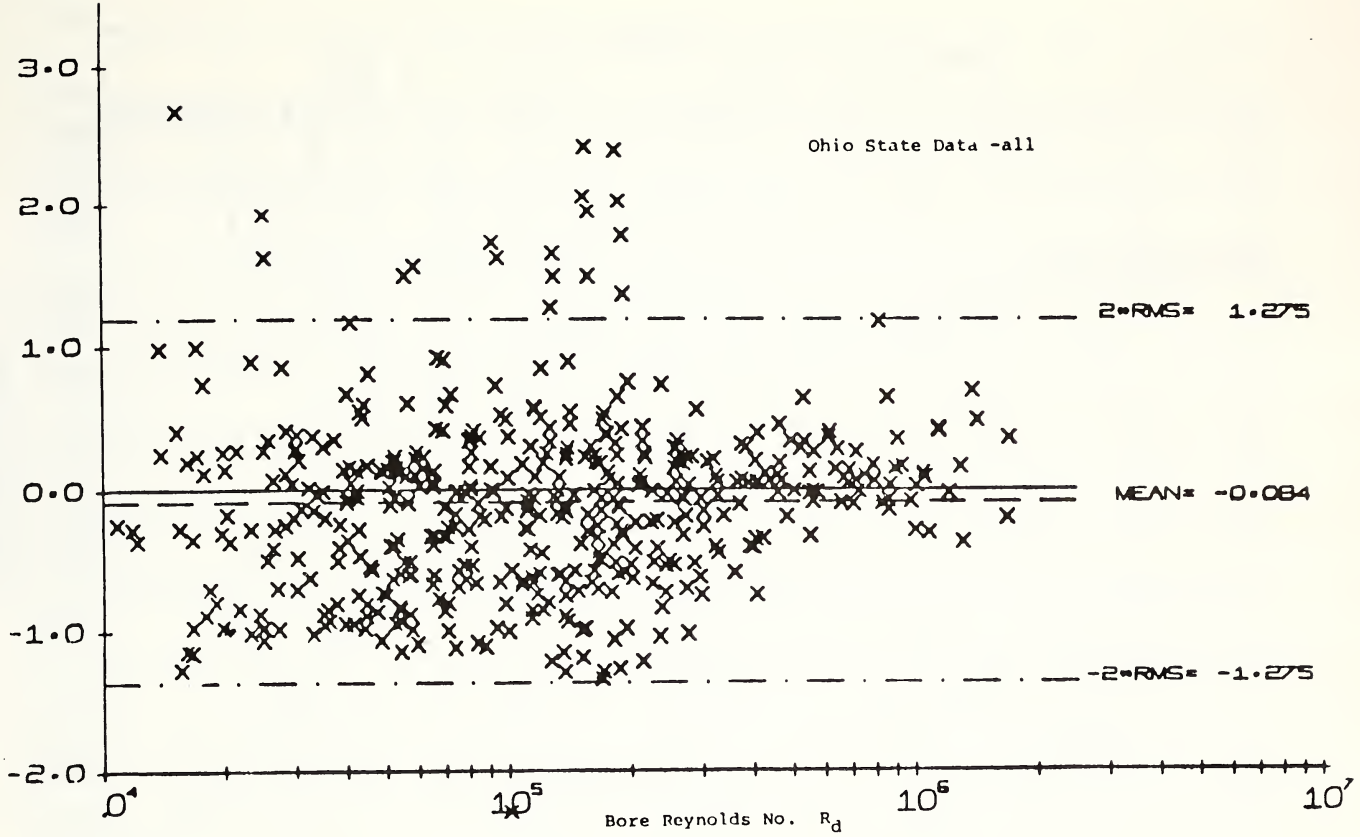

Ohio State Data -all
2•RMS= 1.275
MEAN= -0.084
-2•RMS= -1.275
3.0
2.0
1.0
0.0
-1.0
-2.0
10^4
10^5
10^6
10^7
Bore Reynolds No. R_d
% = $[(C-C_{AGA})/C_{AGA}]$ x 100

FIGURE 3

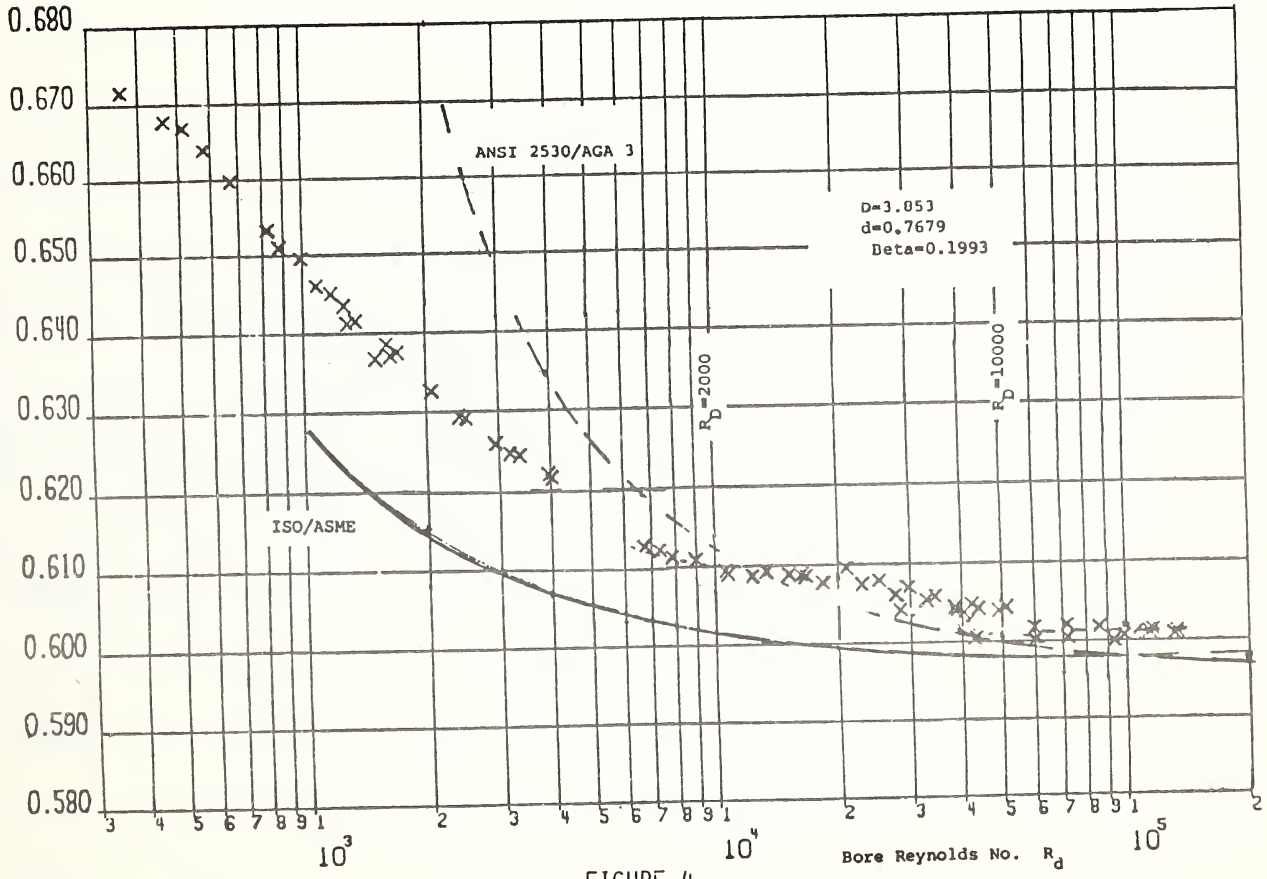

0.680
0.670
0.660
0.650
0.640
0.630
0.620
0.610
0.600
0.590
0.580
Discharge Coefficient
ANSI 2530/AGA 3
D=3.053
d=0.7679
Deta=0.1993
R_D=2000
R_D=10000
ISO/ASME
3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2
10^3
10^4
10^5
Bore Reynolds No. R_d

FIGURE 4

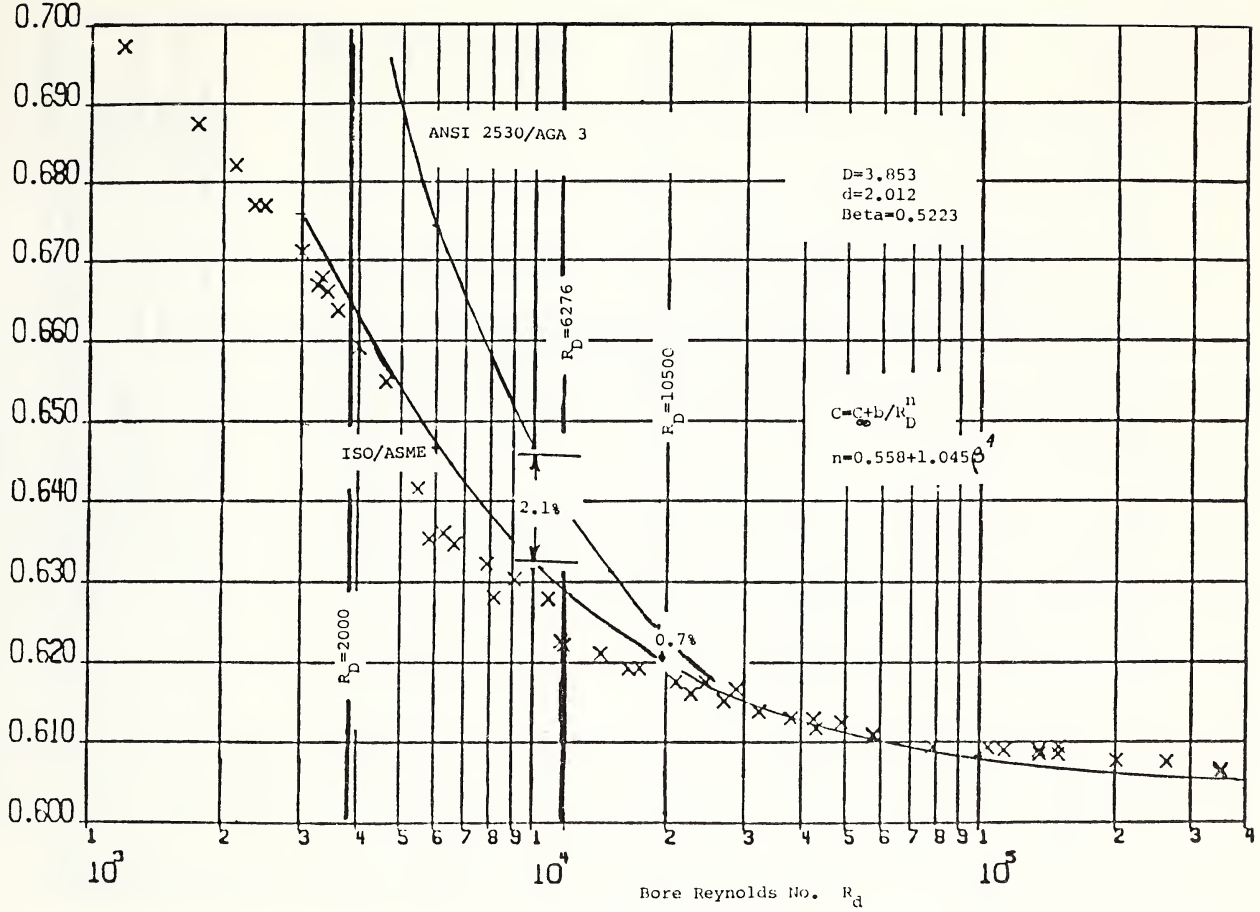

0.700
0.690
0.680
0.670
0.660
0.650
0.640
0.630
0.620
0.610
0.600
Discharge Coefficient
ANSI 2530/AGA 3
ISO/ASME
D=3.853
d=2.012
Beta=0.5223
$C=C_\infty+b/R_D^n$
$n=0.558+1.045\beta^4$
R_D=6276
R_D=10500
R_D=2000
2.1%
0.7%
1
2
3
4
5
6
7
8
9
10^3
10^4
10^5
Bore Reynolds No. R_d

FIGURE 5

The Foxboro and Daniel data are combined with the 303 OSU data points (Miller, 1979) used to obtain the Stolz equation and are shown plotted in Figure 6 as the percentage difference between each data point and the Buckingham (AGA-3, 1955) equation. The data show a bias of +0.23 from the coefficient predicted by the Buckingham equation and a poor correlation at the lower Reynolds numbers. Earlier work by the author (Miller, 1979) has shown that a systematic shift of 0.3% in the prediction equation produces a fitting equation with an uncertainty of $\pm$0.46% (except at low Reynolds numbers). Figure 7 contains the same data as used in Figure 6 except now plotted as the deviation of each test point from the Stolz (1977) equation. It can be seen that the overall agreement is improved with the results now falling within a two sigma bandwidth of $\pm$ 0.5 percent with the bias reduced to + 0.14 percent.

Orifice plates are used by engineers in a variety of situations including applications other than the custody transfer of natural gas. In fact, it is estimated that for every orifice used on natural gas there are more than 20 used for other applications. Any standards promulgated must also be useful to these applications as well. Information is needed for flows at Reynolds numbers down to 2000 for a wide range of fluids and pipe sizes, temperatures and installations. Some data exist that should be considered in determining a suitable equation fit. For example, these would include the oil data of the Oklahoma tests (Ambrosius, E.E., 1937). There would result an increase in confidence that the results of flow measurements for conditions appropriate to these other applications would actually be within the claimed uncertainty band.

Natural gas metering applications require substantial extrapolation of the original data and questions have been raised over the decades since the 1930's as to whether extrapolation to higher Reynolds numbers using the Buckingham equation is justified. The discharge coefficient data are limited to a range of Reynolds numbers from 20,000 to 2.5 million. But natural gas at custody transfer points is usually at Reynolds numbers between 20 million and 40 million. Tests at Hilvarenbeck in The Netherlands (Gorter et al, 1977) in the early 1970's, like those at Refugio (AGA, 1954) in the 1950's, were designed to determine if extrapolation to these high Reynolds numbers is justified. On the basis of the Hilvarenbeck tests, the Reynolds number was raised to 100 million in ISO 5167. It is not clear, however, whether the tests have really proven this conclusion to be valid within the uncertainty limits given in that ISO standard for all beta ratios.

Laboratory bias

There is an apparant advantage to using the OSU data base in that all the tests were carried out in one laboratory. In such a case, idiosyncracies and biases between laboratories, which often cause systematic offsets in the results, are substantially reduced. However, it should not be concluded that the resulting data are therefore the most reliable. The use of a single laboratory introduces a systematic error in the data which is difficult to assess. In fact, with the meter runs being tested coming from one manufacturer, with the pressure difference instrumentation the same throughout

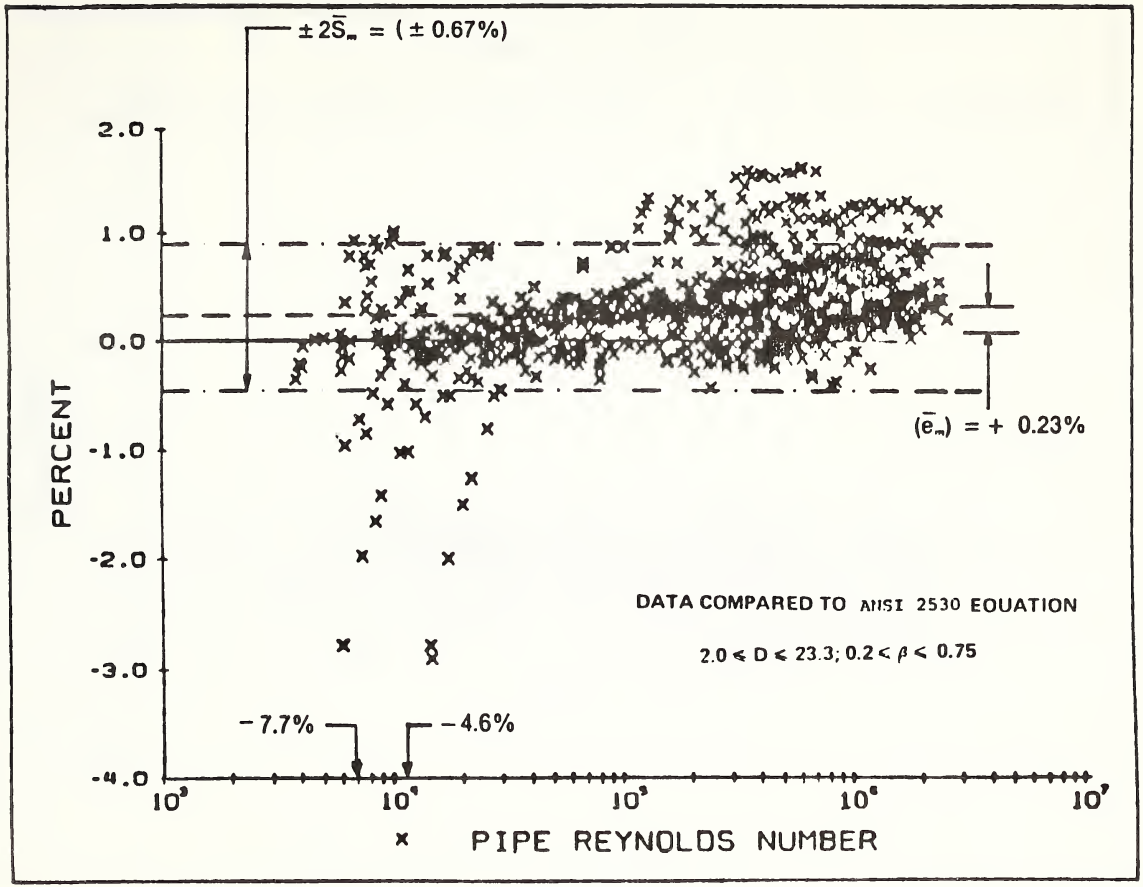

± 2S̄m = (± 0.67%)
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
PERCENT
(ēm) = + 0.23%
DATA COMPARED TO ANSI 2530 EQUATION
2.0 ≤ D ≤ 23.3; 0.2 < β < 0.75
- 7.7%
- 4.6%
10³
10⁴
10⁵
10⁶
10⁷
PIPE REYNOLDS NUMBER

FIGURE 6

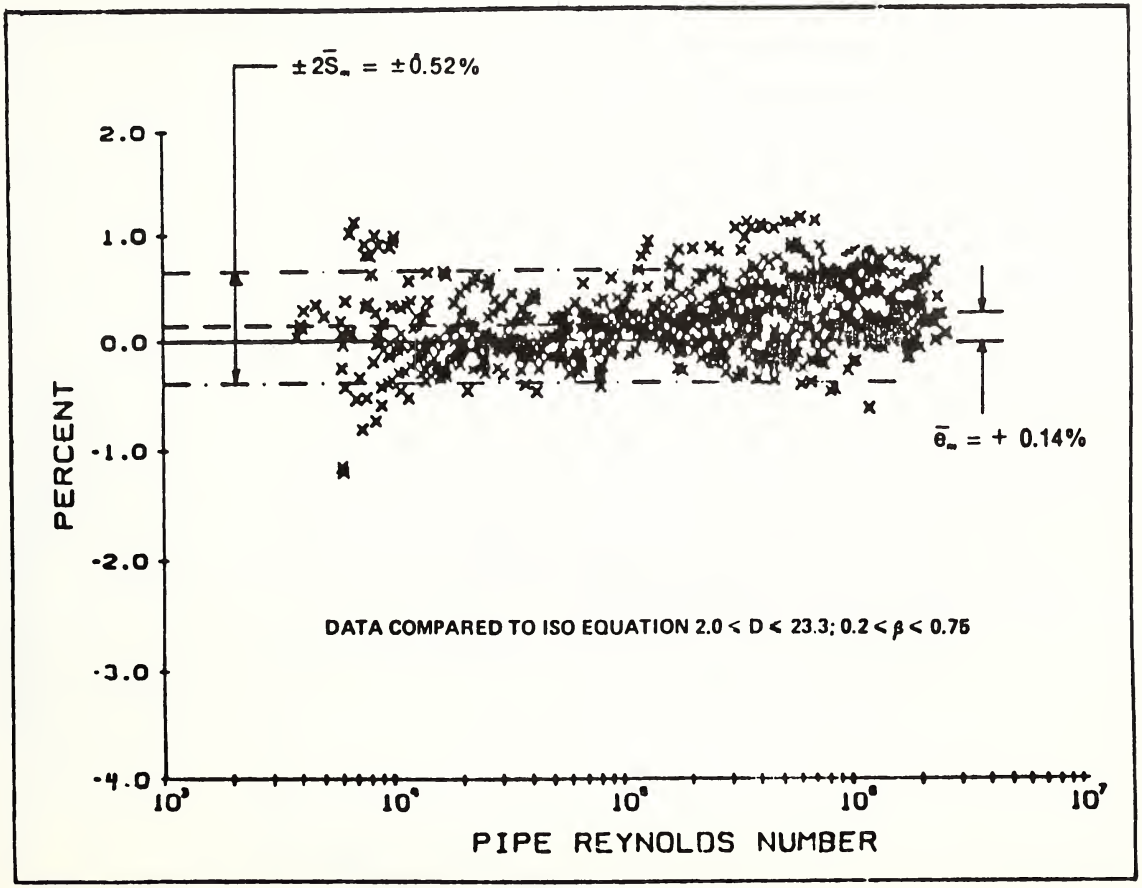

±2S̄m = ±0.52%
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
PERCENT
ēm = + 0.14%
DATA COMPARED TO ISO EQUATION 2.0 < D < 23.3; 0.2 < β < 0.75
10³
10⁴
10⁵
10⁶
10⁷
PIPE REYNOLDS NUMBER

FIGURE 7

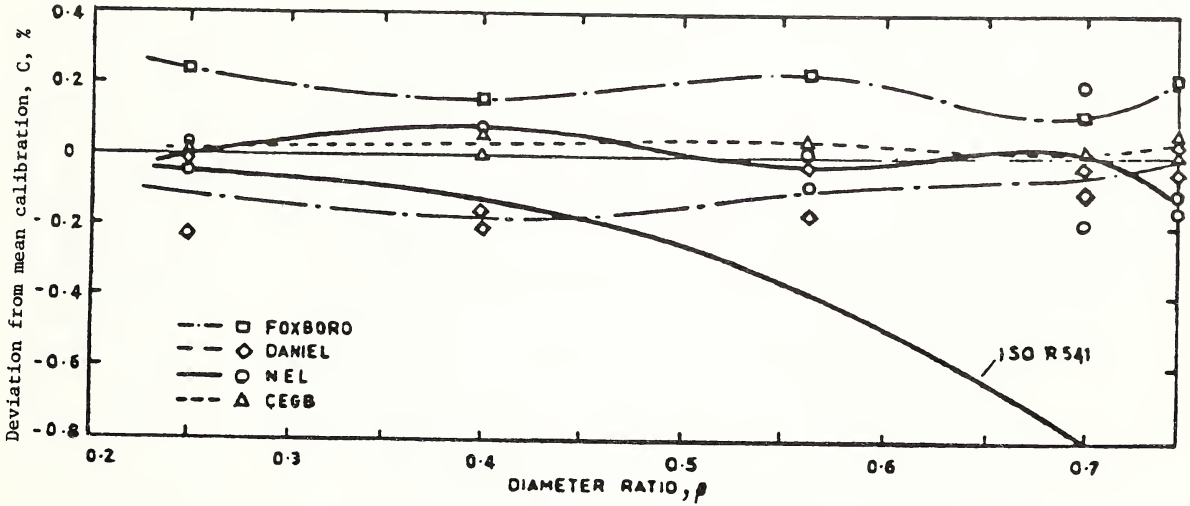
the test programs, with the use of one test laboratory, and with many other parameters constant, a combination of systematic errors accumulate which could result in a sizeable offset from the true values in the coefficient data.

Figure 8 shows the results from a major intercomparison of a series of tests among four organizations that collaborated in that study. These included the Foxboro Company and Daniel Industries in the USA and the NEL and the Central Electricity Generating Board in the U.K. (Levie et al, 1978). The results from each laboratory follow its own pattern. Results based on flange taps showed an increasing divergence from both the values given in the ISO 5167 and the Buckingham (AGA) equation. This has increased the concern that the OSU data may not be representative of orifice meter runs in current use.

Accuracy

In practice there are four different ways for stating accuracies. First there is the accuracy claimed for tests carried out at the laboratory under carefully controlled conditions. The uncertainty values given for these are naturally the smallest, in the same way that the uncertainty associated with the measurement of the standard kilogram is far smaller than that associated with the reference kilogram used in the office of the local weights and measures inspector. Another accuracy statement is associated with the in-situ calibration of a flowmeter, such as obtained from using a ball prover to check a turbine flowmeter. Here again high quality equipment and personnel are generally involved but loss of accuracy is increased over that achieved in the laboratory because of the inability to control all of the measurement conditions. For example, there can be a reduction in the stability of the flow being measured as compared to the flow produced under best laboratory conditions. There can also be a degradation in accuracy due to climatic variations at the measurement site, etc. A third accuracy statement used is that which is agreed upon by the buyer and seller in a custody transfer agreement. These are applicable to the flow measurement as detailed in the contract between buyer and seller. This can lead to a method of measurement for which the accuracy as stated might be quite artificial. In this the true flow rate or total flow may not even be known nor, in fact, even need to be known since the contractual agreement might call for the automatic acceptance of the indication of the flow meter regardless of its accuracy. Finally there is an accuracy statement which is best described as "caveat emptor" - buyer beware. This accuracy statement is often fictional and it is left up to the buyer to accept or reject it.

In almost all operational situations, it is impossible for a meter user to carry out an in-situ calibration. He does, however, need to have an indication of the extent to which he can trust his measurement. Estimates of the overall accuracy need to be made on each measured variable, and these then statistically combined to estimate the overall uncertainty. A wider error band than indicated should be postulated in order to take into account all the variations which exist between the user's particular measurement process and the conditions under which the laboratory measurements were originally made.



Refugio Orifice Plates - Flange Tap Calibrations.
Comparison Between Laboratory Results

FIGURE 8

Reynolds Number

It has, to this point, been assumed that the Reynolds number calculated using the simple equation for fluid velocity, density, and viscosity in a given pipe is a fundamental flow parameter. The accepted rationale states that all data will fall on a single unique coefficient-Reynolds number signature curve. This enables the coefficients derived from measurements on water at lower Reynolds numbers to be applied to natural gas. It has to be recognized, however, that, while the Reynolds number is a valuable concept, it is not as comprehensive as it is often assumed to be. For example, the Reynolds number criterion applied to fully developed flow in a very long straight pipeline may be the same for smooth and rough pipe but the velocity profiles are quite different.

In practice, the velocity profile is often found to be distorted and asymmetric so that its effect on the pressure distribution around the orifice plate changes dramatically from that obtained for a fully developed velocity profile. Similarly, turbulence level variations and pulsating flow often result in substantial shifts in the discharge coefficient even though the calculated Reynolds number remains unchanged.

Orifice Plate Influences

A serious problem associated with the use of orifice plates, or for any differential producer, has to do with how the pressure is measured. This relates to the effect of pressure fluctuations and flow variations near the locations of the pressure taps. Work by Rayle (1959) showed the importance of the pressure tap geometry and how geometric variations can lead to pressure measurement errors. Other investigators have shown that the pressure tap must be sufficiently long to avoid errors caused by recirculation in the piezometer ring.

The uncertainties associated with these factors must be taken into account before an overall error estimate can be obtained. Effects produced on the flow by drain and vent holes drilled through the orifice plate to prevent the build-up of debris or entrained liquids must also be considered. Many users of this technique to control liquid and debris build-up have not been aware of problems so introduced. The coefficient of the orifice plate can change significantly because of these holes especially if the hole associated with the pressure tap is in the same sector of the plate as is the drain hole.

At the present time, the permitted eccentricity between orifice bore and pipe centerline is a matter of considerable discussion. The problem originated when the requirement given in the ISO standard was found to be so stringent that orifice meter run manufacturers had a great deal of difficulty in meeting the requirements, particularly in small diameter pipes. In fact, this requirement has had to be relaxed because in practice the tolerances allowed for the flange locations in relation to the pipe center line were greater than those for the allowed plate eccentricity.

Variations in coefficient with orifice plate thickness is shown in Figure 9. The effect of increasing the thickness of the orifice plate to the point where the streamlines are no longer free within the plate bore is illustrated in Figure 9. At the other extreme, decreasing the plate thickness leads to a plate which bends under the differential pressure across it. The distortion resulting from such bending can be predicted for the various techniques used to clamp the plate. Figure 10 shows the effect of bending on the discharge coefficient. The orifice edge should be square and sharp. All too often edge sharpness is cursorily checked before installation and in many industrial applications, the plate is never checked again, even though edge erosion often occurs. The effect on the discharge coefficient of variations in edge sharpness is dramatic as shown in Figure 11 (Benedict et al, 1974).

Pipe fittings and characteristics of the pipeline also have an effect on the discharge coefficient. It can generally be stated that increased errors are experienced with the higher beta ratios (Miller, 1979). As regards the effect of the pipeline itself, there is a general agreement that the predicted coefficient will only be obtained when sufficient length of straight pipe is installed ahead of the meter.

There are those who dispute the existence of the influence of roughness for the range of roughness allowed by the standards. However, there may be considerable variation between results obtained in rough and smooth pipes, see Figure 12 (Starrett, 1965). Little work has been reported in recent years on the effects of plate roughness. It is clear, however, that it is important not to allow the plate surface to roughen in use, see Figure 13 (McVeigh, 1962). The extent of the roughening permitted needs to be established.

As soon as there is a disturbance in the flow, such as that due to a fitting upstream, or when the pipe is not straight, a velocity profile change occurs and swirl may be introduced. Swirl is easy to induce and very difficult to eliminate. The natural decay of swirl requires great lengths of straight pipe, often hundreds of pipe diameters. ISO 5167 limits the swirl angle to two degrees though swirl is very rarely, if ever, measured in practical installations. The user generally relies on the tables and figures given in the standards. These give distances from the fittings beyond which it is considered safe to install the orifice meter. The standards do not state that swirl decay is a function of Reynolds number so the adequate length of straight pipe to reduce the swirl to an acceptable level at one Reynolds number may not be adequate at another Reynolds number. This clearly needs more investigation, since it is normally accepted that the Reynolds number has no influence on the installation effects.

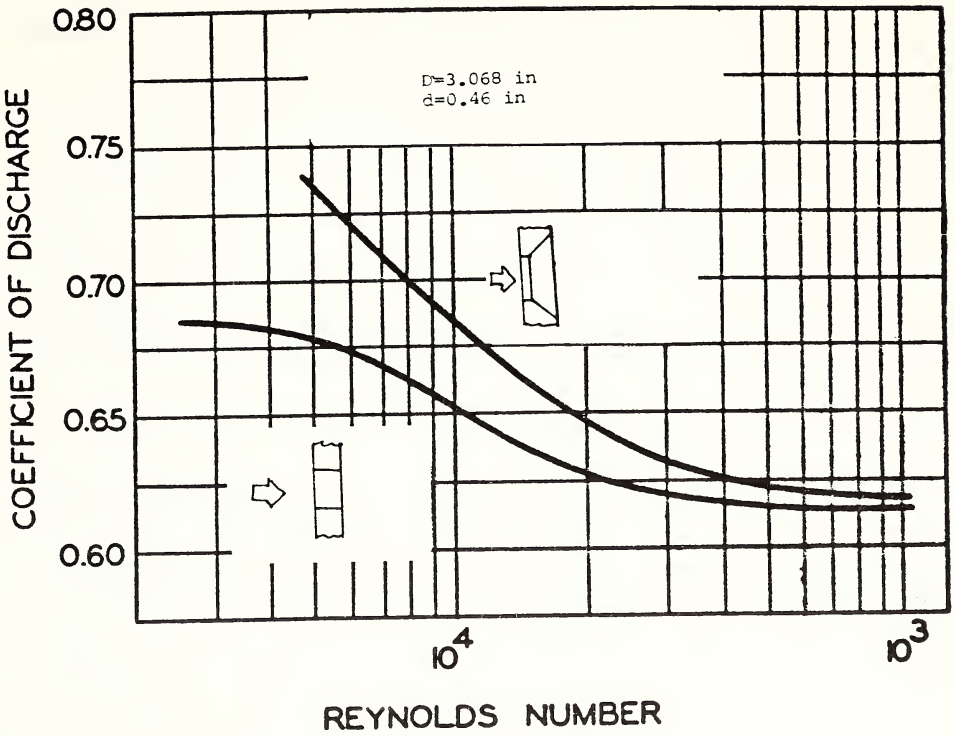
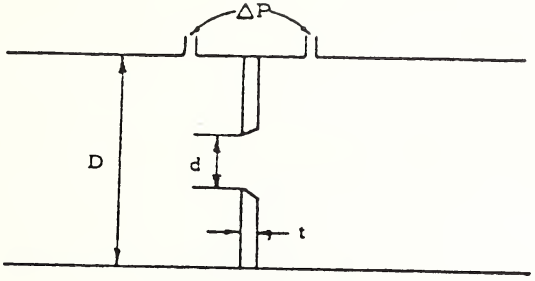
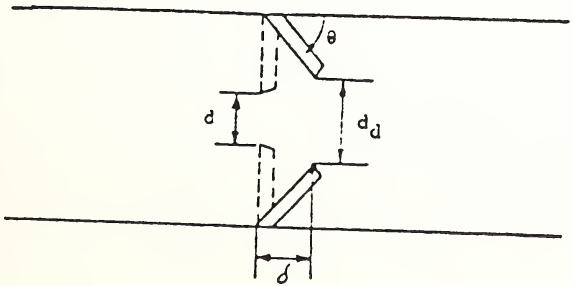

0.80
0.75
0.70
0.65
0.60
COEFFICIENT OF DISCHARGE
D=3.068 in
d=0.46 in
10^4
10^3
REYNOLDS NUMBER

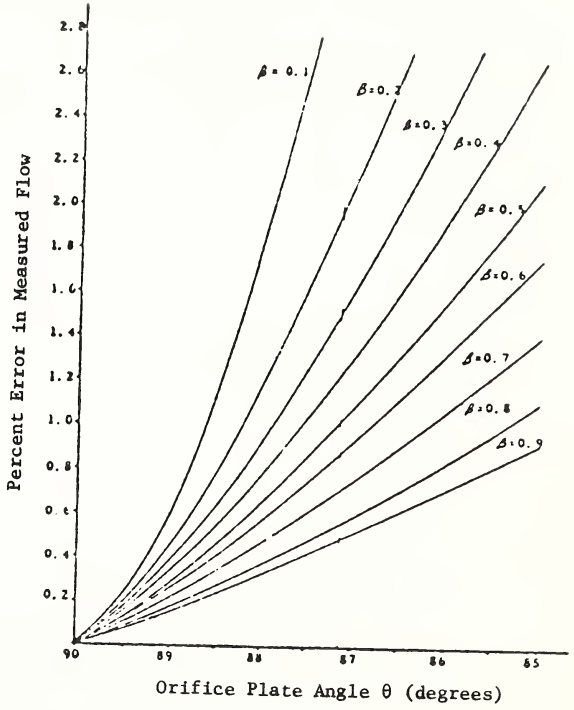
FIGURE 9



Undeflected Orifice

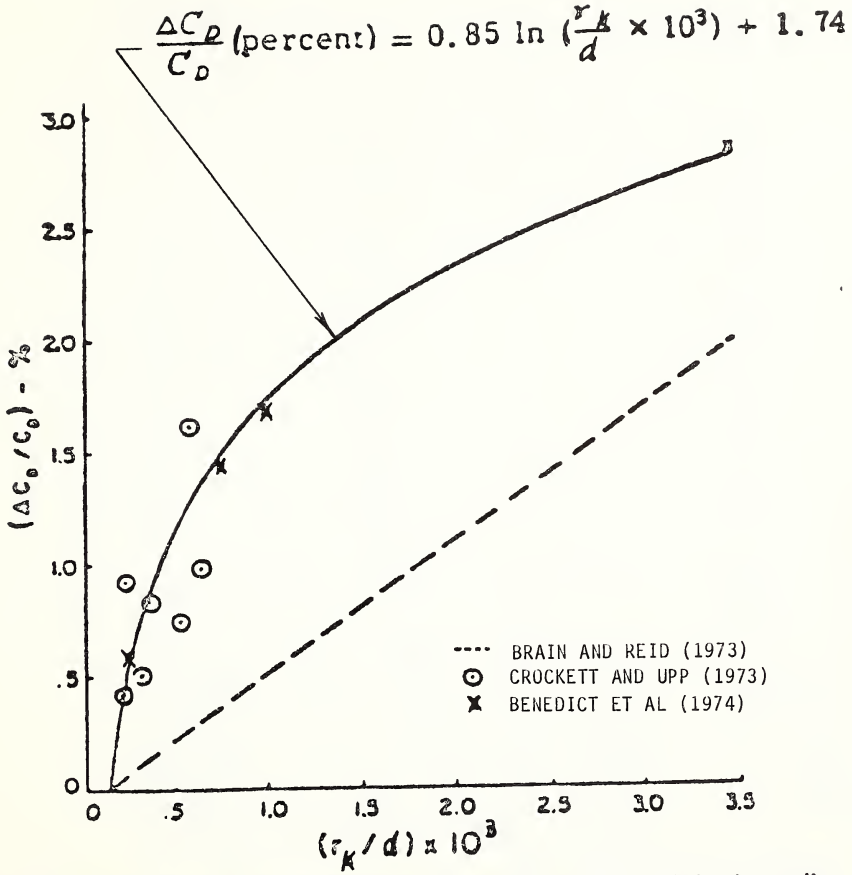


Deflected Orifice



Measurement Error versus Orifice Plate Angle

FIGURE 10



Comparison of edge roundness—discharge coefficient results

FIGURE 11

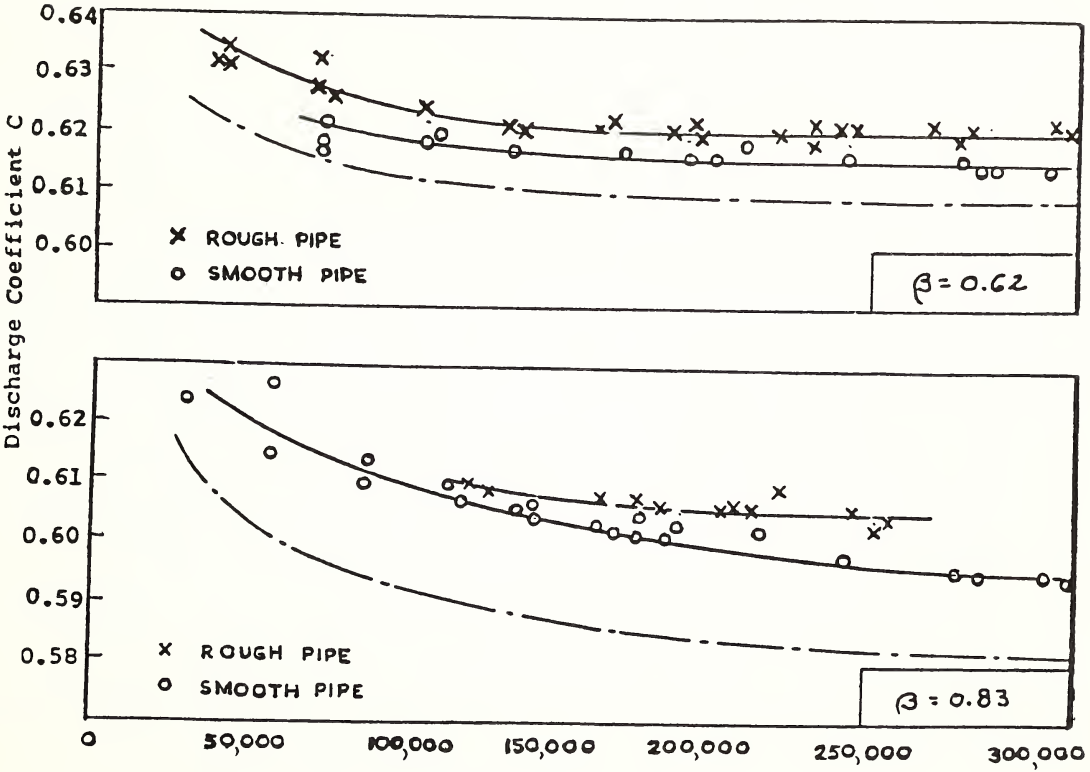

Discharge Coefficient C
0.64
0.63
0.62
0.61
0.60
ROUGH PIPE
SMOOTH PIPE
β = 0.62
0.62
0.61
0.60
0.59
0.58
ROUGH PIPE
SMOOTH PIPE
β = 0.83
0
50,000
100,000
150,000
200,000
250,000
300,000
Bore Reynolds No. R_d

FIGURE 12

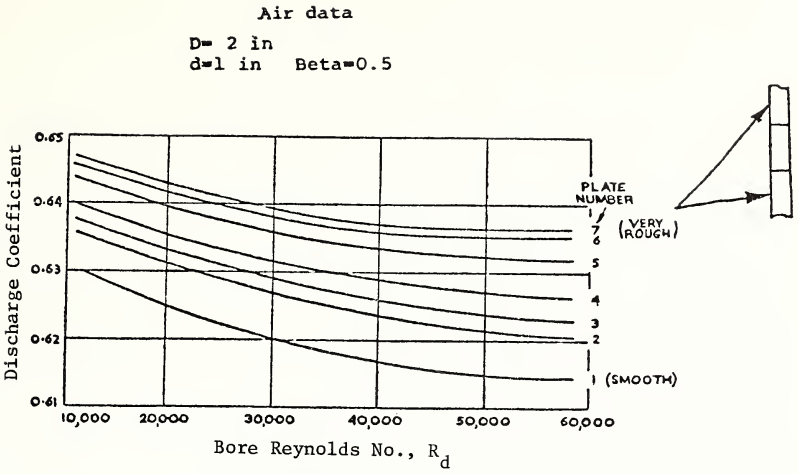


FIGURE 13

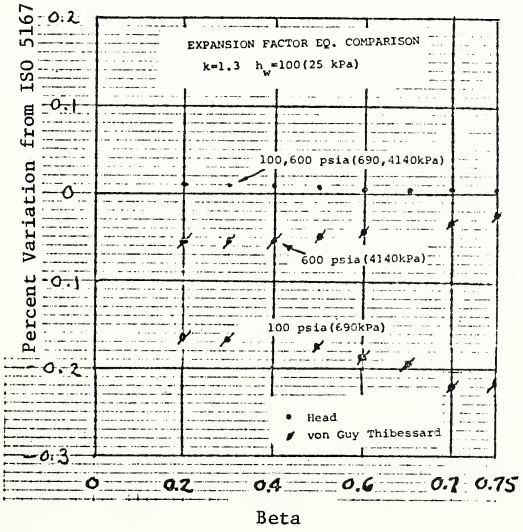


FIGURE 14

There has been considerable discussion of the substantial differences between the lengths of straight upstream pipe required by AGA Report No. 3 and those given in ISO 5167. These differences resulted from different criteria being used in the analyses of the data carried out in Europe and in the USA. In the USA, the criterion specified a required length which did not cause the discharge coefficient to differ by more than $\pm$0.5% from that obtained for an infinitely long straight pipe installation. The required lengths obviously vary with the limiting value set for the coefficient change. It is believed that the AGA report values were associated originally with a 0.5 percent shift while the European tables were based on a 0.2 percent criterion. This may not be the total explanation for the differences between these standards but can certainly account for much of the problem. It must be recognized, however, that whatever the approach adopted for the resolution of the differences in the standards, the percent shift criterion associated with the installation limit must be added to the assessment of the overall uncertainty. This percentage should not be assumed to be part of the uncertainty associated with that obtained for the discharge coefficient measurement under carefully controlled laboratory conditions.

Which pressure tap, i.e. corner, flange, or D and D/2, is least sensitive to installation conditions is of practical importance. Some believe that corner taps are most sensitive to upstream disturbances, but that the differences are not large enough to justify changing from one tapping arrangement to another.

Straighteners

Many view the use of flow straighteners as a panacea for solving all problems associated with variations in installation conditions. AGA only recommends a vane type straightener for all disturbances (ANSI 2530, 1978). Results obtained at the author's laboratory with 83 diameters of straight pipe upstream of the orifice as compared to those obtained with an AGA straightener with double bends upstream by the required distance showed less than a 0.25% difference. On the other hand, there are examples where installing a straightener relatively close to the orifice plate even with no disturbance upstream resulted in a significant shift in the discharge coefficient. It must be concluded that additional work is needed to determine the effect and value of flow straighteners on the discharge coefficient. Probably each type of straightener will require a different location and its own length of straight pipe.

Gas Expansion

The gas expansion factor was referred to earlier in this paper. A systematic bias associated with the factor equations is evident. The work by Thibessard (1960) predicts a value lower by 0.2 percent than that of Head or Buckingham, see Figure 14. Further there is an indication that other changes exist for natural gas.

Pulsating Flow

A review of the current state-of-the-art of orifice metering must include a discussion of the problem of measuring flow when pulsations are present. It is,of course, impossible to have a flow field which is completely steady. We have already touched on the subject of turbulence and fluctuations earlier. Pulsating flow occurs when such fluctuations follow a regular pattern. This results in quite serious errors being generated. It is a good operating maxim that when pulsating flow is suspected, or where pulsating flow can be seen from the pressure difference fluctuations, that a new meter site be selected. It is almost certain that, in the presence of pulsating flow, accurate measurements cannot be made no matter what technique is used to suppress pulsations at the secondary device. Nevertheless, there are instances where it is not possible to find a suitable location to place the orifice meter and measurements must be made in the presence of pulsations. There are ways in which the adverse effect of pulsations can be reduced, if not eliminated. The methods generally used are based either on introducing capacity into the pipeline or by producing a high pressure drop.

Conclusions

In a general sense, it must be recognized that there are many practical problems associated with orifice metering. The examples given have shown that there are a number of areas where there is still doubt as to whether the constraints associated with present standards are adequate. Yet the standards are becoming increasingly more complicated and hard to meet. It is certainly clear that further investigations are necessary in order either to confirm or to correct the intent of the procedures given in these standards. An attempt to design a purely empirical program of testing to study the various effects described above immediately shows a need for an extremely large number of tests and hence for very extensive resources and a substantial amount of time. Each effect considered above requires a series of tests so that the sum over these is in itself substantial. Some reflection will show that each effect is related to the properties of the fluid stream either as produced upstream or as affected by some aspect of the plate design. The presence of two problems, therefore, leads to an interaction between (and some kind of summation over) two modifications of the fluid stream. Under such conditions each effect will be tested under conditions which are quite different from those present when that effect was tested by itself. This means that conclusions as to the measurement results obtained from these various effects in the field might require a testing program involving the simultaneous presence of combinations of the various effects described above. The total number of combinations being quite large, the number of tests required then is substantial. This would seem to suggest that this problem cannot be solved by a testing program alone but requires some combination of fundamental measurement, numerical modelling and testing. The reader should keep this in mind when reading the following two papers.

A major problem on which considerable additional attention needs to be focused is the level of uncertainty which should be attributed to the values of the discharge coefficients obtained in the field. Obviously, the relationship of the equations used to the test data to which they are fitted can be improved and the associated uncertainty between predicted values and laboratory test values reduced. It does not necessarily follow, however, that the uncertainty associated with data obtained at a practical installation is the same as that associated with these values predicted from the equation in the standard.

Despite all the criticisms which can be applied to it, and all the problems we have described, the orifice plate meter remains a very reliable and useful device for measuring rate and quantity of fluid flow. It is clear, however, that in the case of the custody transfer of natural gas, where highest accuracies are demanded, sufficient accuracy and sufficient confidence in the results obtained can be had only if further research of the flow phenomena associated with the device is carried out. This will make it possible to know which aspects of the meter's use must be made more rigorous and which can be relaxed, or to determine even if the orifice and its associated secondary equipment can be expected to yield $\pm$ 0.5% in-situ accuracy.

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FUNDAMENTAL FLOW RESEARCH - POTENTIAL FOR CONTRIBUTING TO ORIFICE METER TECHNOLOGY

G. E. Mattingly
Senior Scientist for Fluid Measurements
National Bureau of Standards
Gaithersburg, MD

SUMMARY

"In the text that follows, it is my intent to make two important points. Firstly, to my colleagues in academia, I want to expand upon several points made in the previous presentation by Mr. Miller and add a few additional points to demonstrate that orifice flow contains a fascinating collection of interesting and important fluid phenomena worthy of academic research attention. Secondly, to my colleagues in the orifice metering community, I want to describe some of the new and very powerful fluid dynamic research tools that are currently available for conducting orifice research e.g., Laser Doppler Velocimetry, hot wire and hot film anemometry, optical and visualization techniques, and computer modeling. The last will be the topic of the following presentation by the Professors Ghia. One can only speculate that if these tools had been available to such orifice meter pioneers as Professor Beitler, Mr. H. S. Bean, Dr. E. Buckingham, and their successors in the U.S. and abroad, it would have been possible for them to complement their calibration results with a thorough and detailed understanding of the significant flow field parameters affecting orifice meter performance. With fundamental information of this kind to guide standards documents and practical orifice technology in place of the empiricism that had to be used, it may very well have turned out that orifice performance might have evolved so satisfactorily that this workshop would not have been needed.

Since these tools were not available until quite recently, it will be my major thesis that orifice research programs must now be initiated to use these tools to their fullest capabilities. With these tools and the understanding of orifice flow that can be obtained with them, improved controls and standards can be produced that could enable the improvements in orifice performance desired by industry to be achieved. The sooner this is begun, the sooner one can expect to attain these goals. The time to begin is now."

Introduction

The rising price of natural gas is producing a corresponding rise in demands for reductions in the uncertainty currently associated with orifice meter measurements. Such measurements are the basis for the custody transfer of this valuable product. The dollar value of unaccounted-for gas resulting from this metering uncertainty is difficult to quantify precisely. Reasonable estimates can be made, however. In the introduction to this report, it is estimated that this is equivalent to perhaps two thirds of a million dollars a day of gas as averaged over the USA annually. It is becoming widely realized that the levels of improvement needed to reduce this uncertainty in metering cannot be achieved using the calibration and testing approaches currently employed in the establishment and confirmation of the present state

of orifice meter technology. There is a growing number of practitioners who feel that the accuracy of orifice measurements can be expected to improve significantly from current levels only when there is a major extension in the fundamental understanding of the fluid dynamics that control the performance of these meters. Early calibration and testing programs as well as subsequent analyses indicate that orifice performance involves a number of highly interactive factors which are being controlled only to certain, specified (and generally inadequate) levels in fundamental terms. Current levels of uncertainty, we are convinced, can be significantly reduced only when these factors are better understood.

Science and industry are now in a position where new intensive studies of these dynamics can be made. Studies are, in fact, being considered which will build on the results of already completed preliminary investigations and which will employ newly available research tools. These experimental tools, which include laser anemometry and high-speed visualization methods, now enable us to attain a level of understanding of orifice flow not previously possible in the laboratory. When these experimental techniques are used in coordination with corresponding collaborative theoretical and computational approaches, it will become possible to analyze and evaluate the relative sensitivity of flow measurement with orifice meters to the many factors that affect it.

Realistic analyses of the flow through an orifice meter must include many hydrodynamical effects which control the performance of the meter. Prominent among these are turbulence, pulsations, instabilities, and coherent structures in the flow. Conventionally, flow through orifice meters has been analyzed by decomposing the fluid motions into time-averaged quantities and then considering perturbations upon these. In this approach, the effects of the perturbations are grouped and only cursorily characterized. Tools are now available - both experimental and computational - with which to decompose these perturbations such that each can be examined separately thereby allowing individual effects to be evaluated. Following on such studies, combined perturbation effects can also be considered, i.e. in pairs, etc. until actual orifice meter performance can be fully and completely understood. Such understanding can then be made part of orifice practice. When this is done and the results implemented in orifice practice, improved performance can be expected.

Background

1. Ideal Orifice Performance

The time-averaged, ideal orifice flow field, shown in Figure 1, has been the focal point of many studies. References (1-21) describe this range of studies and some of the results obtained from them. These have shown conclusively that the orifice flow field is altered by a number of effects. This ideal flow pattern is perturbed by fluid dynamic instabilities, coherent structures, turbulence, and pulsations. These sources of deviations affect the flow and pressure distributions shown in Figure 1, causing them to deviate from those

ORIFICE FLOW - THE AXISYMMETRIC IDEAL

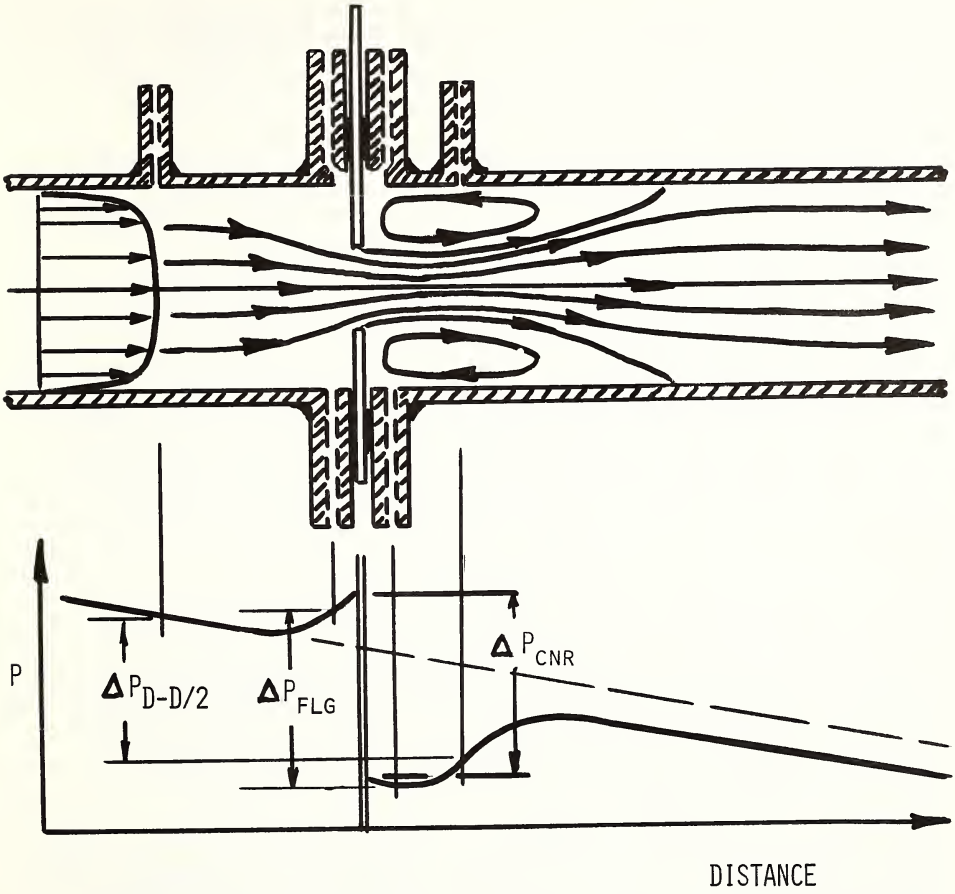

FIGURE 1

assumed in deriving the metering equations in use. This affects the accuracies and performance of the orifice meter. Because instabilities and coherent structures can develop naturally in the orifice jet and because the turbulence distributions in the flow field are inherent to the flow in this geometry, we shall confine our attention to these aspects.

Pulsation effects as transmitted from specific sources, such as valves, pumps, and compressors, etc. are dependent on the characteristics of these sources. For this reason, these will not be dealt with in the discussion that follows. References (22-26) present current descriptions of the effects of pulsations on orifice meters and on other differential pressure type meters.

Because the fluid inertial effects in most pipelines far exceed viscous effects, orifice flows are predominantly turbulent. As a result, the pressure distributions along the pipewalls have a corresponding randomly varying component which can significantly affect the level of uncertainty and the accuracy of flow measurements with orifice meters.

For incompressible, one-dimensional, steady flow, the conservation of mass and energy relationships can be used to produce the theoretical mass or volumetric flowrate that will occur though the orifice constriction from a high pressure upstream to a lower pressure downstream. The actual flow rate can be computed using a discharge coefficient, C_D and the theoretical flowrate as follows:

$$Q = \frac{A_d C_D}{\sqrt{1-\beta^4}} \sqrt{\frac{2\Delta P}{\rho}}$$

where, in compatible units, Q is the volumetric flowrate, A_d is the orifice hole area, β is the orifice hole to pipe diameter ratio, ΔP is the pressure difference, and ρ is the fluid density. The discharge coefficient is dependent on the orifice geometry, a sequence of dimensionless flow parameters, and the specific installation. The deviation of the discharge coefficient from unity can be considered to be a measure of the deviation of actual conditions from the assumptions involved in applying the above described conservation equations to orifice flow.

2. Perturbations on Ideal Performance

Deviations from ideal conditions can result from anomalies in pipe geometry, plate geometry, and inlet flow. Pipe geometry includes pipe size, shape, roughness, alignment, as well as pressure-tapping and measuring arrangements, see (27, 28). Each of these anomalies can increase or decrease the orifice discharge coefficient. Similarly, orifice plate size, shape, roughness, flatness, edge sharpness, and concentricity can significantly affect meter performance. Consequently, prevailing discharge coefficients can be expected to be significantly larger or smaller than predicted values in particular installations depending on the nature and amount of the particular deviations present.

The effects of plate bending are sketched qualitatively in Figure 2(a). Bent orifice plates change the beta ratio and the flow pattern in the meter. The pressure differential produced across the undeflected orifice plate (shown by the solid lines) causes it to deflect into the configuration as shown by the

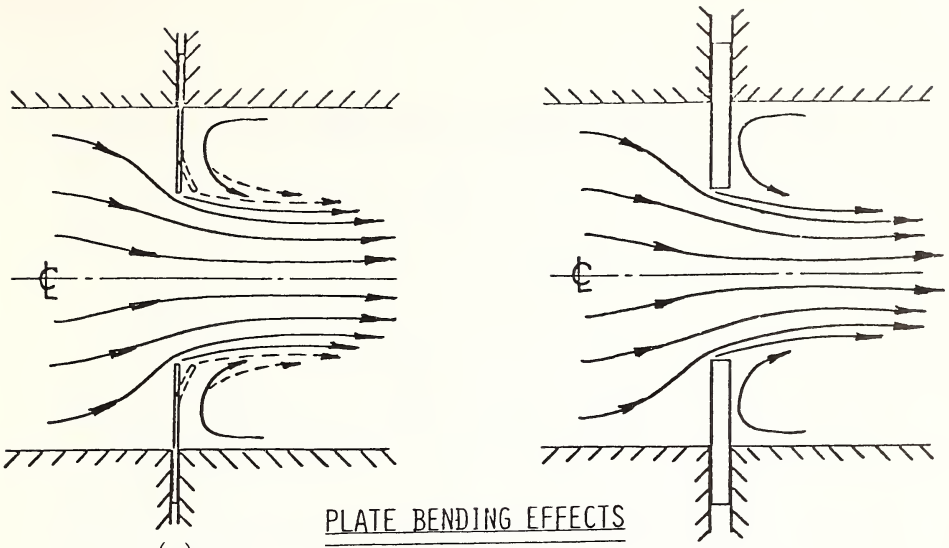

FIGURE 2

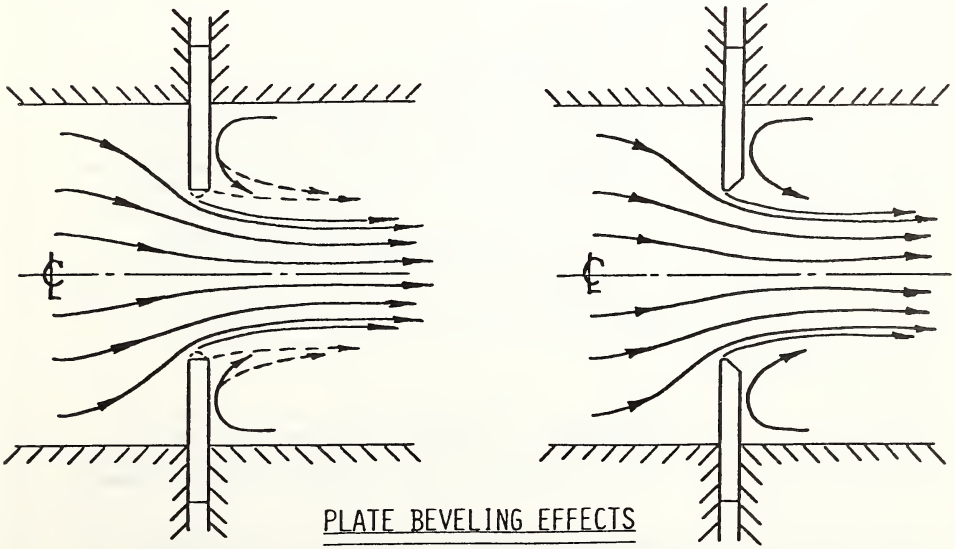

FIGURE 3

dashed lines. This deflection (or a bent orifice plate) could reduce the stagnation pressure sensed at the upstream tap location which could, in turn, increase the discharge coefficient, see (29). The separation streamline from the orifice edge for these respective configurations is also sketched. The deflecting (or bent) orifice plate affects the flow downstream of the plate which in turn affects the pressure at the downstream tap. The relative amount of this pressure change will depend on the tap location. Both the plate deflections and the streamline displacements are shown qualitatively to illustrate plate bending effects.

Because orifice plates have finite thicknesses, the initial plate bending reduces the beta ratio. This would tend to decrease the discharge coefficient. However, continued deflection can have the effect of enlarging beta which would then tend to increase the discharge coefficient. If plate deflection does not exceed the elastic limits of the plate material, then reducing the flow to zero restores the plate to its unbent configuration. Thus, for a specific plate, deflection versus flow characteristics should be repeatable if elastic limits are not exceeded. For different plates, however, where geometries, materials, and conditions such as temperature may change, particular variations can be expected accordingly. Fluctuations in the flow due to turbulence, pulsations, etc., will produce corresponding time varying effects superimposed on the effects of plate deflections, hence on the associated flow field, and on the pressure distribution imposed upon the inner pipe wall and the differential pressure measuring system. Taken together these can be expected to modify the effective flow measurement as indicated by the metering system.

One method for reducing plate bending effects involves using thicker plates, as shown in Figure 2(b). This solution for reducing the uncertainty associated with plate bending can produce additional sources of metering uncertainty. The orifice flow through a thick plate is sketched in Figure 3(a). The preferred, or assumed, flow pattern is that shown by the solid lines. However, because of the thick orifice edge, the flow separating from the upstream edge of the plate can reattach itself as shown by the dashed streamlines. Differences in the respective, time-averaged, flow patterns can be expected with systematic changes then occurring in the discharge coefficients. As well, the time varying aspects of the flow pattern can add further to the associated unsteadiness in the measured pressure differential. Figure 3(b) shows a solution to this problem. By removing downstream orifice edge surface by beveling, as shown, the flow pattern associated with the thicker plate can then be stabilized and the metering uncertainties commensurately reduced.

Significant changes in predicted discharge coefficients can be produced by anomalies in inlet flow distributions. Anomalies can occur: (1) in the profile of the streamwise component of the flow velocity or (2) through the presence of one or more types of swirl that can be induced by piping elements upstream of the meter.

Reductions or expansions in the pipe diameter upstream of orifice meters can affect discharge coefficients. The flow effects produced by these piping elements are sketched qualitatively as shown in Figure 4(a). The pipe contraction produces favorable streamwise pressure gradients that accelerate

INLET FLOW - LINEAR VELOCITY

Effects of Pipe Transitions

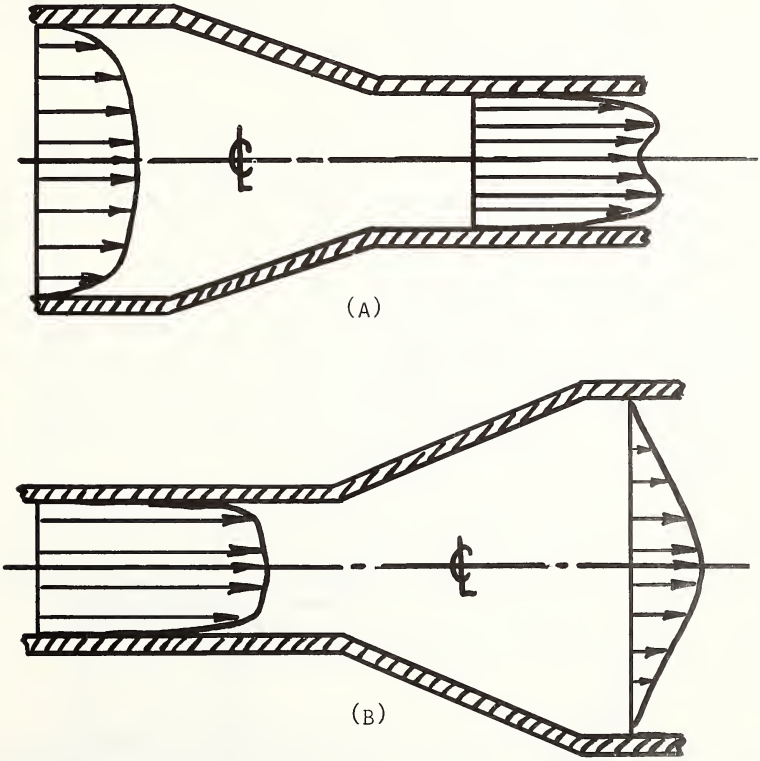

FIGURE 4

fluid layers adjacent to the pipe wall. If the lengths of straight pipe that separate the pipe contraction and a meter located downstream are not sufficiently long so that these acceleration effects are diffused, the meter's discharge coefficient can be radically altered. For example, accelerated fluid layers adjacent to the pipe wall can increase the pressure sensed at the upstream tap thereby decreasing discharge coefficients.

Similarly, through pipe enlargements, the adverse pressure gradients produced cause decceleration of fluid layers near the pipe wall. This can lead to profiles of the type shown qualitatively in Figure 4(b). These flows would tend to reduce pressures sensed at the upstream tap location thereby resulting in increased discharge coefficients.

The effects that elbows have on pipe flow profiles are sketched in Figs. 5(a) and 5(b). In Fig. 5(a) a single elbow is shown to produce a dual eddy, secondary flow pattern. The stability and dissipation of this pattern with downstream distance is not well known. An orifice meter positioned so as to measure a flow in this pattern will be affected by it depending upon the orientation of the pressure tappings with respect to this secondary flow pattern, see (30-34).

Fig. 5(b) sketches the secondary flow pattern for the configuration known as "elbows out of plane". It is widely held in metering practice that this configuration produces a significantly energetic, single eddy, secondary flow pattern that requires long pipe lengths to allow dissipation of this swirling eddy. An orifice meter placed too near this piping configuration could sense very high pressures at its upstream taps because of the swirl effects. This elevated pressure field would tend to reduce the prevailing discharge coefficient. This, in turn, would produce meter readings that are less than they should be, i.e., the meter would "under-read".

Calibration and testing projects have been carried out to produce data that characterize orifice performance in a variety of installations, see (30-34). These results can be used to estimate the perturbations produced on the performance of meters placed too closely to elbows, pipe diameter changes, or partially opened valves. As well, these results form the basis for recommending meter installations where these perturbing influences have been diffused either naturally or through flow conditioning.

3. Flow Conditioning

Flow conditioning philosophies vary as do the associated devices. An excellent review is given in (35). A prevalent flow conditioning philosophy is to remove artificially those flow anomalies which affect orifice meter performance.

Tube bundle flow straighteners, which consist of large numbers of small tubes are quite prevalent. These bundles, which are several pipe diameters in length, are placed upstream of orifice meters so that, through "wave-guiding" action, they reduce secondary motions such as sketched in Figs. 5(a) or 5(b).

INLET FLOW - SWIRL VELOCITY

EFFECTS OF AN ELBOW

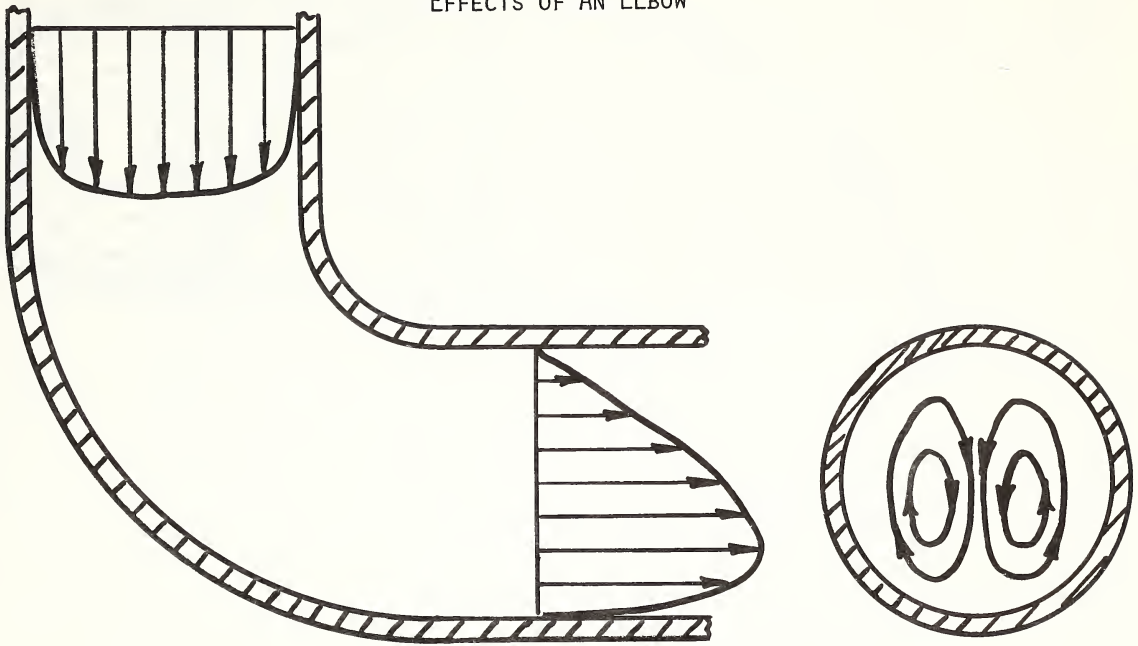

FIGURE 5(A)

EFFECTS OF TWO ELBOWS

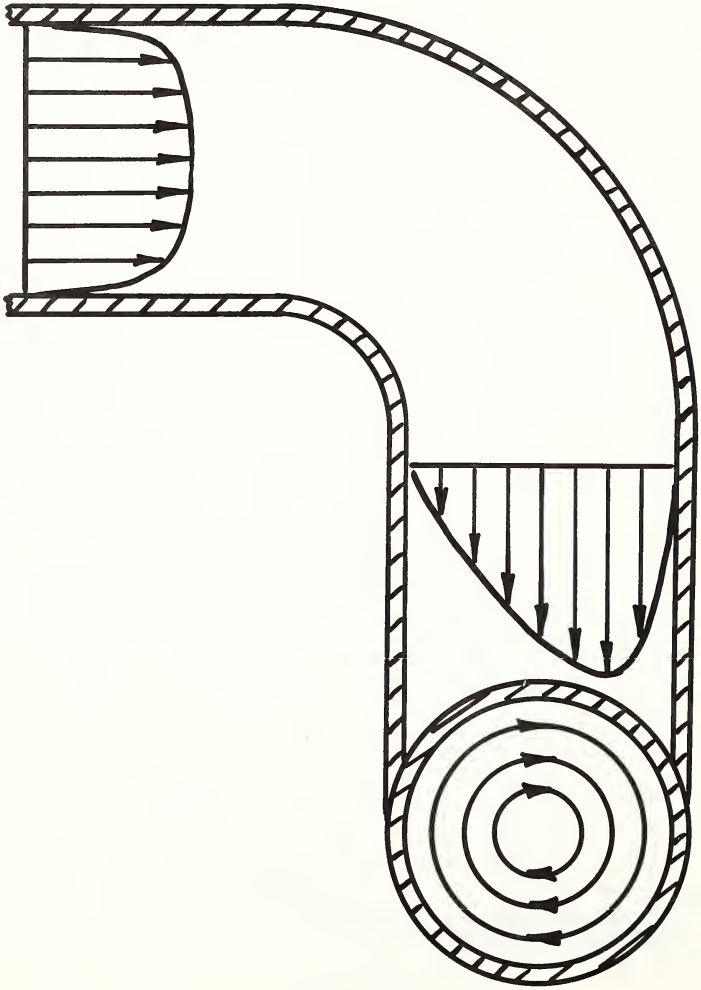

FIGURE 5 (B)

The tube bundle's effectiveness in reducing swirl reduces the need for long lengths of straight pipe. Similar to tube bundle straighteners are the "slat-type" and the "Etoile" straighteners. These use wave-guiding action produced by small square or triangular passages produced by assemblies of flat plates.

Sprenkle* flow conditioners consist of multiple discs, usually three , having large numbers of small holes drilled through them. These discs are supported across the cross-sectional area of a pipe flow to produce highly turbulent wakes. These wakes are designed to mix the fluid kinetic energy so that swirl is diffused and the streamwise component of the velocity profile closely resembles a "fully developed" pipe flow profile - i.e., that which would evolve naturally via very long lengths of straight pipe.

A Zanker-type flow conditioner is basically a combination of a single Sprenkle disc followed by a "slat-type" straightener. It is designed to construct a "fully developed" pipe flow distribution through selected disc hole sizings aligned with each channel of the straightener, see (36). A design somewhat similar to the Zanker type device is becoming known as the Mitsubishi flow conditioner (37).

Using computer modeling techniques to calculate the flow fields through reasonably simple flow conditioning geometries, NBS staff have produced a configuration that shows good conditioning potential. This conditioner turns the pipe flow through four 90° turns and includes passing the flow through a cylindrical surface containing small holes. The resulting tortuosity produces very repeatable flow profiles in only a few diameters downstream of this device regardless of the anomalies in the distribution of the streamwise flow velocity entering the device, (38). This approach uses the second conditioning philosophy of attempting to produce an extremely repeatable flow profile regardless of that which enters the conditioner. In this manner, once the flow conditioner and meter are calibrated (or otherwise characterized) as a unit, the combination can be expected to produce extremely reliable measurements.

Thus, our short review shows that orifice discharge coefficients can be affected by a number of factors. These can interact with one another to produce combined effects which, in turn, can either enhance or offset their individual effects on the discharge coefficient. Assessing the significance of these effects individually is very difficult - especially if only calibration and testing procedures are used. Assessing their significance in combination is virtually impossible in light of the extremely large number of separate tests then required. Since these effects readily interact with one

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*Device patented by R. E. Sprenkle at Bailey Meter Co., Wycliffe, Ohio.

another through the fluid medium, their effects on prevailing discharge coefficients should be significant. Despite these limitations, testing programs have been extensively used to date to characterize the performance of orifice meters. This is understandable in light of the fact that the capabilities available in fluid research for observing the fundamental fluid phenomena in orifice flow were severely limited. It is our purpose here to show that this is not the case today and that techniques are now available to measure and study these phenomena and their effects on a fundamental level.

Early Orifice Testing

To produce a practical orifice technology, early investigators used calibrations and special tests to characterize orifice phenomena in terms of meter performance - i.e., the discharge coefficient. References. (30-31) contain lists of such testing programs as sponsored in the U.S. by American gas industries. Significant contributions to these programs were made by E. Buckingham and H. S. Bean of the National Bureau of Standards. Equally extensive testing programs were carried out in Europe, including laboratory intercomparisons to enhance the validity of these data sets, see (39,40). Each of these efforts involved the calibration of orifice meters over a range of parameters to determine characteristic performance and to form the basis for installation recommendations and specifications.

Empirical formulae have been fitted to the orifice data developed through the pioneering work of Prof. S. R. Beitler and coworkers at Ohio State University beginning in the 1920's and 30's to provide predictive performance (41-43). These formulae have formed the bases for two standards (31,44). These have provided users with the abilities (at various, accepted levels) to undertake the custody transfer of natural gas and other fluids. However, as the demand and price of gas has increased radically in recent years, buyers and sellers alike feel it is timely to attempt to reduce, significantly, the levels of uncertainty associated with orifice measurements (45),

> "...AGA Report No. 3 (ANSI/API 2530) ... has a stated accuracy of precision of plus or minus 0.5% ... with gas selling at 20 cents a thousand cubic feet and unaccounted for running consistently at less than 0.5% (closer to 0.2%), the industry and those in responsible charge did not have a basis for additional basic research in this area."

In the 1980's, with the natural gas industry delivering approximately 20 trillion cubic feet of gas to U.S. customers annually, uncertainties at the $\pm$0.5% level can correspond to gas quantities at the 100 billion cubic feet level yearly. At costs of 2-3 dollars per thousand cubic feet, this would amount to $200,000,000 per year! Even systematic errors at the level of 0.01% produce biases amount to $4,000,000 yearly. These estimates are considered to understate the situation in that the gas is measured up to six times between well-head and point of consumption and hence the estimates need to be multiplied by a factor of up to six!

New Research Opportunities

To reduce current uncertainty levels associated with orifice measurements, it will be necessary to understand the basic fluid phenomena that control orifice performance. In addition, it will be necessary to understand how the sources of the various performance perturbations mentioned above affect these phenomena.

To attain both of these objectives, it will be necessary to go beyond the technical approaches used in the past. New techniques will be needed, especially the experimental and computational ones that are now available for these studies. Some of the experimental techniques intrude into the flow field to obtain desired measurement; others do not. Table 1 lists a number of each type.

TABLE 1

EXPERIMENTAL TECHNIQUES FOR ORIFICE FLOW

A. INTRUSIVE

1. PITOT TUBES

2. ANEMOMETRY
   - o Hot Wire
   - o Hot Film

3. VISUALIZATION
   - o Smoke Wire
   - o Electrolysis

B. NON-INTRUSIVE

1. VISUALIZATION
   - o Dye Injection

2. OPTICAL
   - o Interferometry

3. LASER DOPPLER VELOCIMETRY

Computational approaches to understanding orifice flow offer tremendous potential because they enable one factor to be changed at a time while holding others fixed and, in fact, offer the possibility of making such changes quite rapidly. In this way, the influence of the various factors on the flow field can be individually assessed in a time period which is short in comparison to the time required to conduct the analogous experiment. Examples of this computational technique can be found in (46,47). When coupled with experimental investigations that are essential to both guide and verify computational procedures and results, this dual approach offers the maximum potential for understanding orifice flow. A description of this powerful research tool is given by Prof. K. Ghia and U. Ghia in the following paper in this report entitled, "On the Role of Computer Modeling in Orifice Research".

Pitot tubes, shown schematically in Figure 6 have the capabilities of measuring the streamwise component of the mean flow velocity distributions, see (48). Care should be taken to measure the fluid velocity without disturbing it. For example, a pitot tube inserted downstream of the orifice plate could disrupt the normal dynamics which occur in the eddy system which resides there.

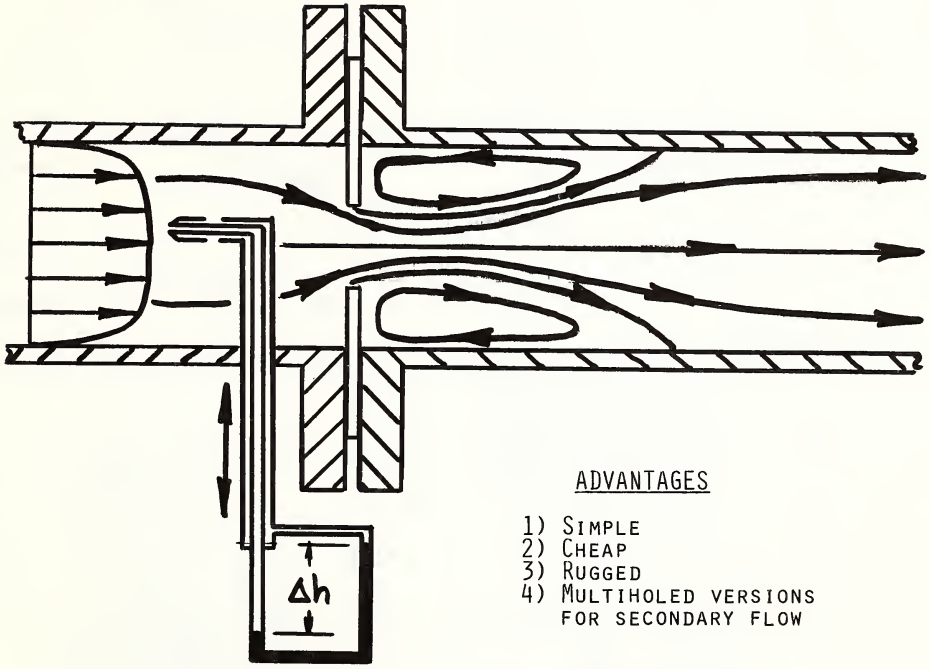
Anemometry techniques which use heat transfer from small elements - hot wires for gas flows and hot films for conducting liquids like water - can measure one or more components of the velocity and are capable of very high frequency response, see (48,22). As such, these can be used to measure flow instabilities, coherent structures, and turbulence. As with pitot tubes, however, care must be used to minimize the intrusive nature of the sensors involved. Figure 7 sketches the way in which the technique could be used to measure streamwise velocity components.

Many visualization techniques have been developed in recent years. Among these, the smoke wire visualization technique is well-suited for use in orifice geometries. Figure 8 shows a configuration that can produce photos of the fluid dynamics in the orifice jet where instabilities and coherent structures can occur. Figure 9 shows typical results using this smoke wire technique. Note the vortices generated at the edge of the orifice jet. The cyclic pulsations produced by these can be transmitted directly to the downstream pressure tap.

Dye injection techniques have been used in orifice meter research (22). Figure 10 shows several arrangements that can be used to picture the fluid dynamics upstream or downstream of the plate.

The hydrogen bubble flow visualization technique uses the electrolysis of water to produce small hydrogen bubbles that, with proper lighting, can be viewed with the naked eye or photographed (49). These small bubbles have a buoyancy to drag ratio that is proportional to the bubble diameter. For sufficiently small bubbles their buoyancy becomes negligible and they become ideal tracers to show fluid motions. By placing the cathode terminal in the

PITOT TUBES



ADVANTAGES

1) Simple
2) Cheap
3) Rugged
4) Multiholed versions for secondary flow

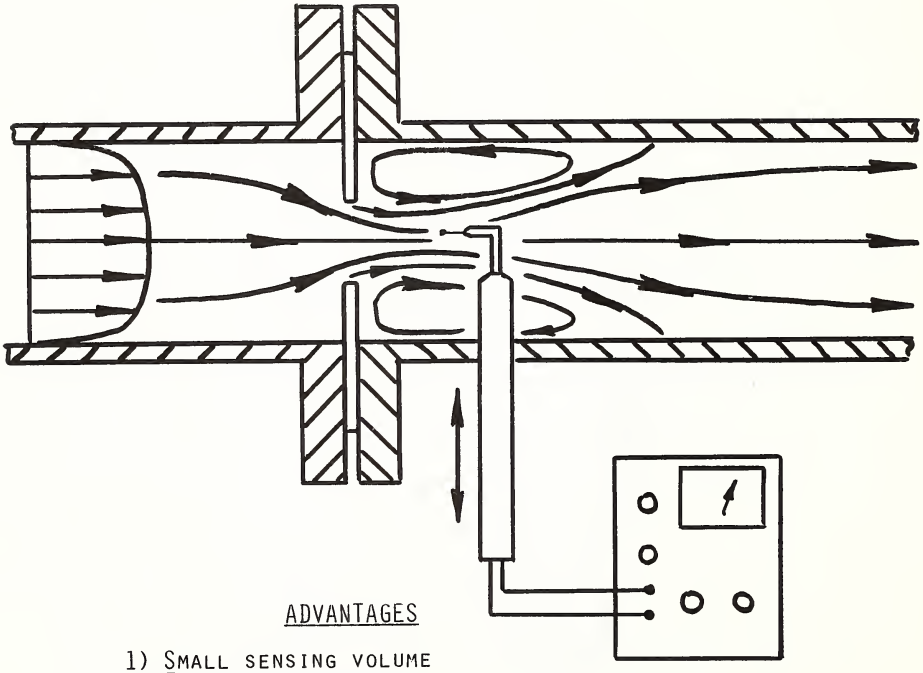
DISADVANTAGES

1) Large sensing volume
2) Non linear principle
3) Slow response
4) Low velocity limit
5) Calibration needed

FIGURE 6

ANEMOMETRY

HOT WIRE AND HOT FILM



ADVANTAGES

1) Small sensing volume
2) Frequency response - very good
3) Multisensor probes

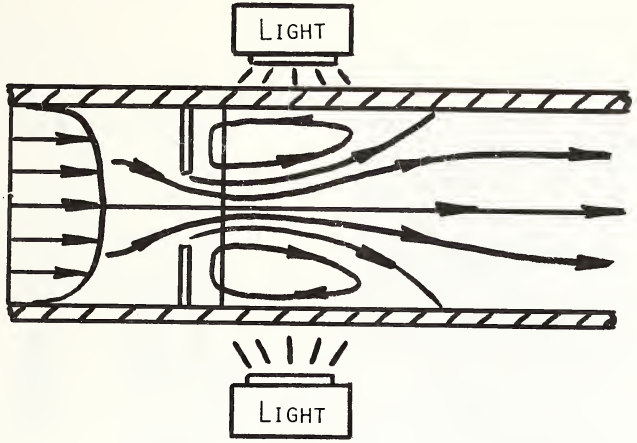
DISADVANTAGES

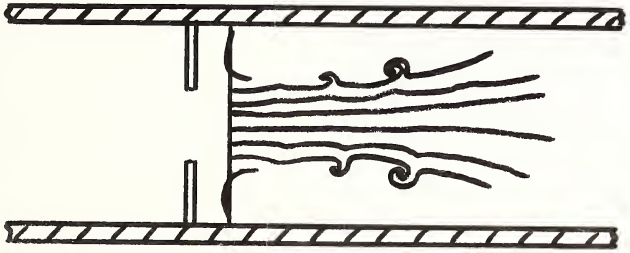
1) Non linear principle
2) Sensors are delicate
3) Low velocity limit
4) Calibration needed

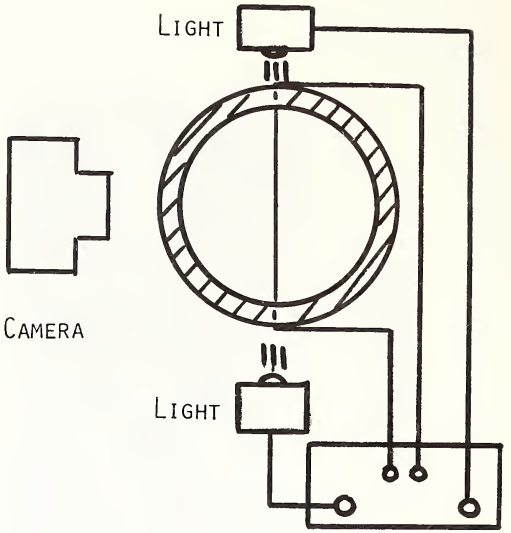
FIGURE 7

VISUALIZATION

SMOKE WIRE







ADVANTAGES

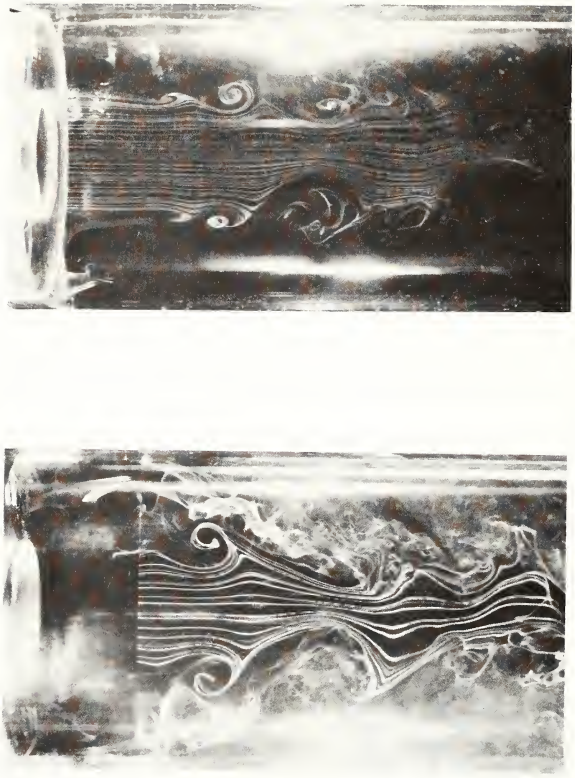
1) MINIMAL INTRUSION EFFECTS
2) QUALITATIVE

DISADVANTAGES

1) LIMITED TO AIRFLOW
2) DIFFUSION LIMITED
3) SHORT "RUN" TIMES

FIGURE 8

SMOKE WIRE RESULTS

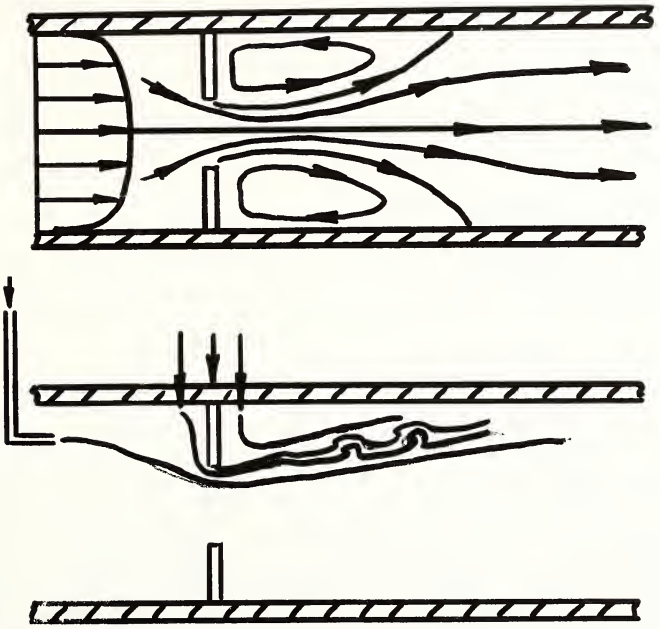


AIR FLOW
4 IN DIA. PIPE
BETA = 0.5
Re_D = 3000

FIGURE 9

VISUALIZATION

DYE INJECTION



ADVANTAGES

1) Simple
2) Cheap

DISADVANTAGES

1) Diffusion Limited
2) Contaminates Fluid

FIGURE 10

form of a thin wire supported where bubble injection is desired and the anode terminal in an inconspicuous location in the flow, visible bubbles can be generated at the cathode using pulsed or d-c excitation. Figure 11 sketches both the electrode arrangements to generate bubbles in a diametral plane as well as the bubble patterns that can be produced.

Laser doppler velocimetry (LDV) is an ideal technique for use in orifice research, see (50). Figure 12 sketches an arrangement of components to measure the streamwise component of the fluid velocity. It is capable, of measuring in a non-intrusive manner, one or more components of the fluid velocity in a field inside the orifice geometry. Because the technique is based on light scattering phenomena, it is capable of very high frequency response. In addition, by using multiple sensing schemes, this technique makes it possible to perform the correlation measurements needed to describe turbulent flow fields properly. LDV is an ideal experimental research tool with which to measure orifice flows. Figure 13 presents typical results from some preliminary velocity traverses measured at NBS.

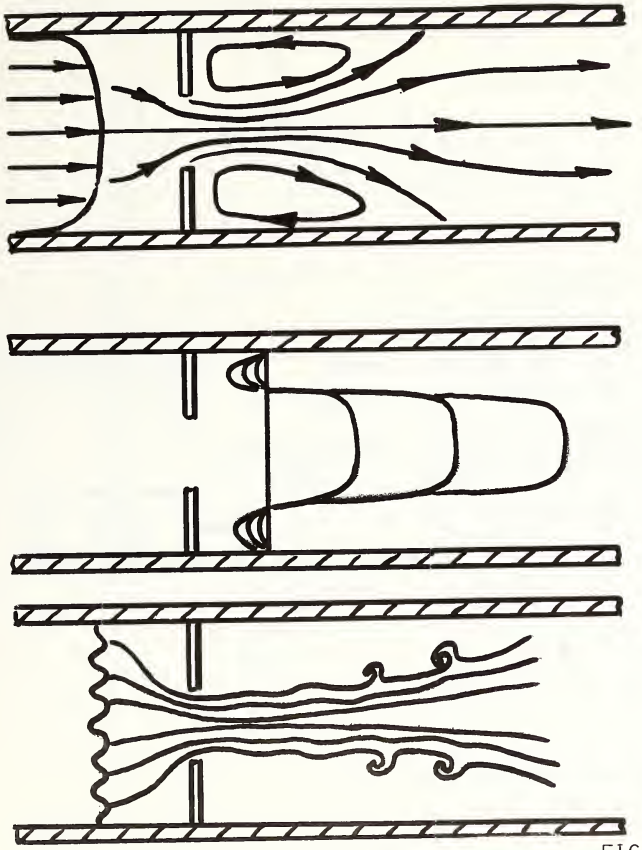
In compressible orifice flow where fluid density variations occur, interferometry is capable of producing, in a non-intrusive manner, both qualitative and quantitative records for orifice flow. Figure 14 sketches an arrangement through which interferometry can be used to give the density field in an orifice flow (48).

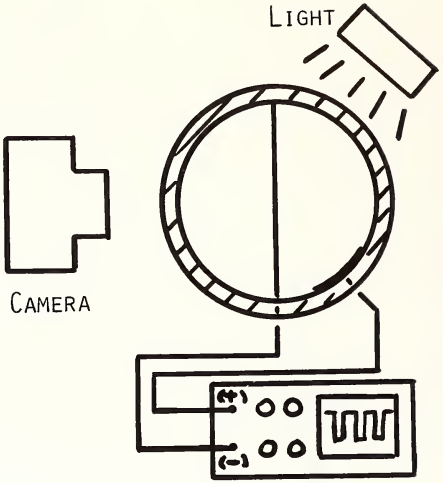
Techniques such as those discussed briefly above, when used in conjunction with corresponding computer modeling efforts, offer immense potential for the attainment of a fundamental understanding of orifice flow. Experimental results, especially those obtained via non-intrusive measurement techniques such as LDV, now enable quantitative descriptions of orifice flow phenomena that were not possible previously. These descriptions will have the three fold benefit of (1) increasing the current knowledge of orifice phenomena, (2) providing essential input to the initiation of computer modeling efforts designed to compute orifice flow, and (3) validating the predictions of the computer model. Once the two approaches (i.e. fundamental flow experiments and computer modeling) are underway, the interactive collaborative efforts are expected to be highly productive in establishing a credible understanding of the factors affecting orifice performance. This understanding, implemented in practice both nationally and internationally via codes and standards, should improve orifice measurements significantly.

Fig. 15 sketches the logo for this Orifice Research Workshop. We have attempted to show that the flow field depicted therein is a fascinating one containing a wide range of interesting and fundamental fluid dynamical phenomena. These phenomena control the performance of orifice meters yet they are far from satisfactorily understood. The extent to which these many factors affect these fluid dynamic phenomena needs investigation to achieve improved understanding of orifice performance and the improvements implemented in orifice practice.

VISUALIZATION

ELECTROLYSIS - HYDROGEN BUBBLE





ADVANTAGES

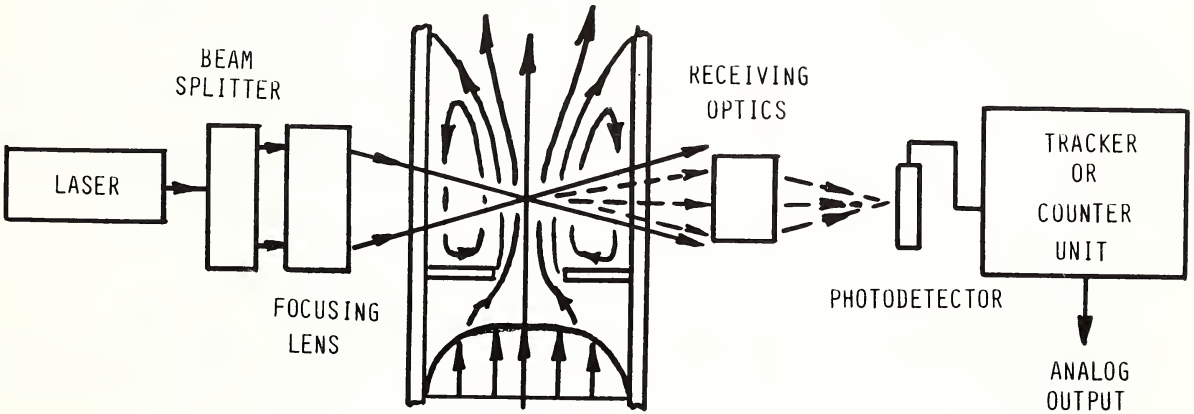
1) MINIMAL INTRUSION EFFECTS
2) QUALITATIVE AND QUANTITATIVE
3) OPERATES CONTINUOUSLY
4) BUBBLES DISSOLVE

DISADVANTAGES

1) LIMITED TO WATER OR WATER MIXTURES
2) WIRES ARE DELICATE
3) VELOCITY LIMITED

FIGURE 11

LASER DOPPLER VELOCIMETRY (LDV)



ADVANTAGES

1) Small sensing volume
2) Frequency response very good
3) Linear principle - measures velocity independent of density, temperature, or composition
4) Measures reversed flow
5) Calibration not required

DISADVANTAGES

1) Optical access required
2) Auxiliary instrumentation delicate

FIGURE 12

(A) D/2 UPSTREAM OF PLATE

(B) D/2 DOWNSTREAM OF PLATE

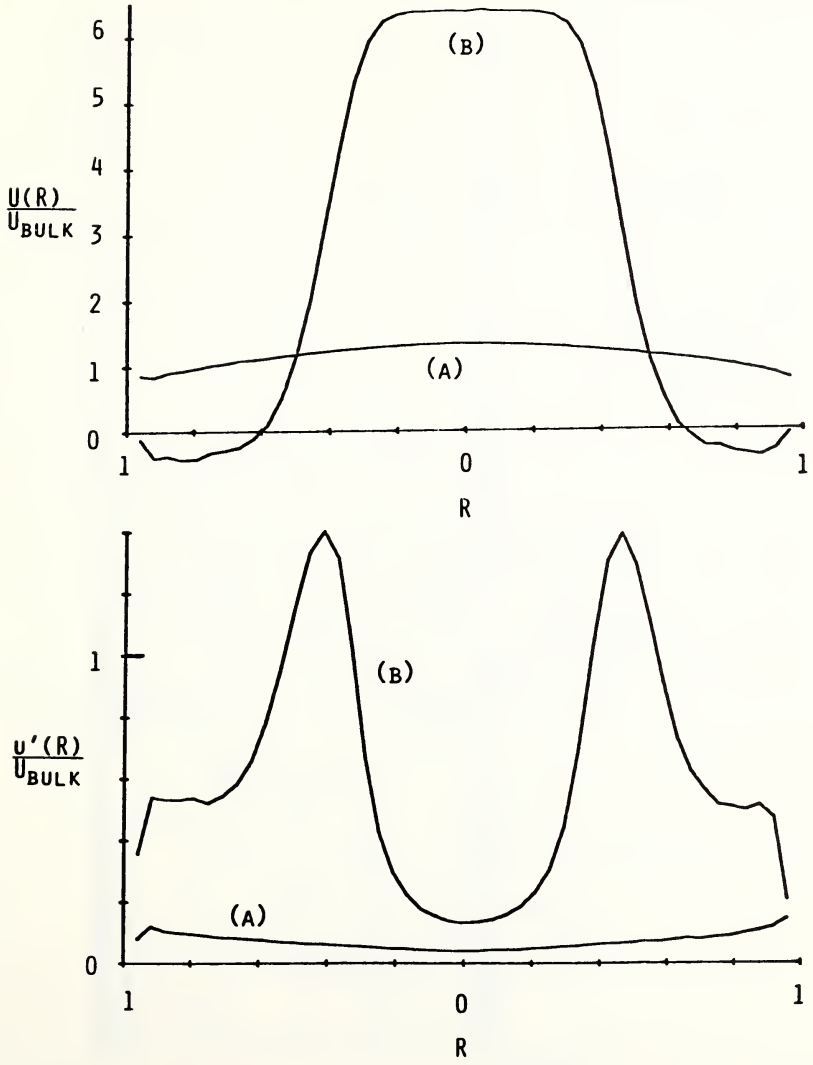
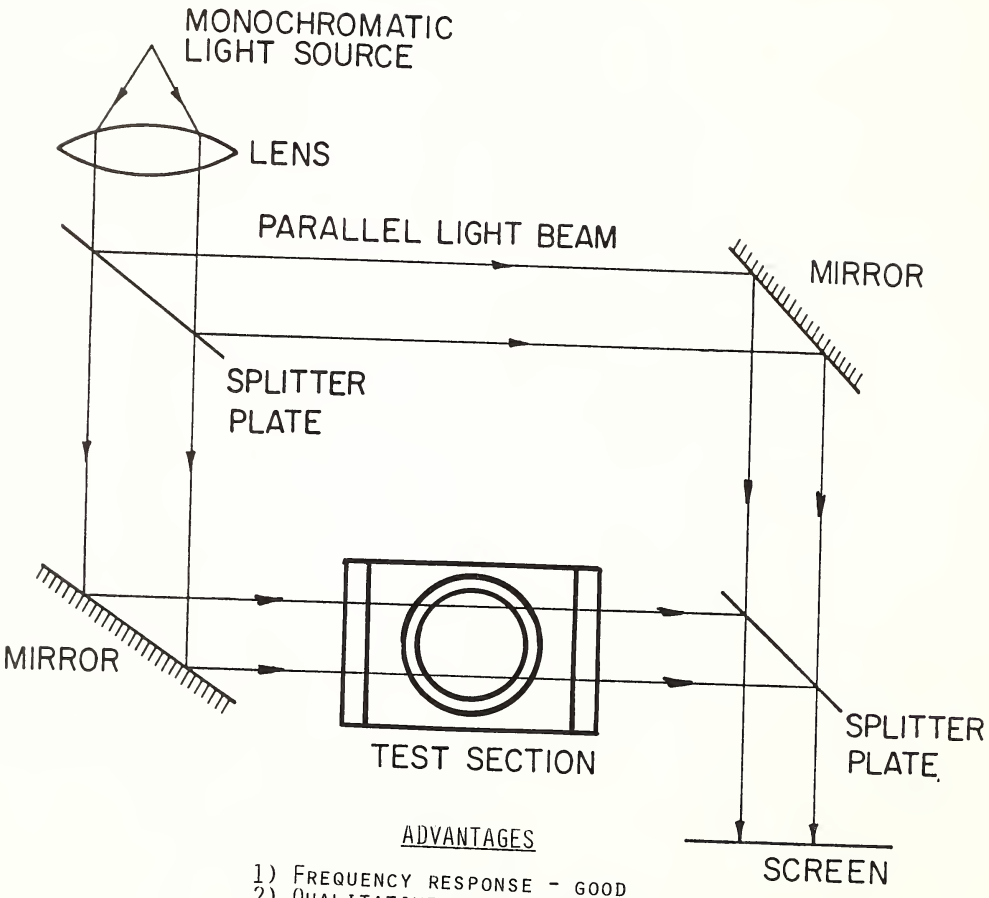


FIGURE 13

INTERFEROMETRY



ADVANTAGES

1) FREQUENCY RESPONSE - GOOD
2) QUALITATIVE AND QUANTITATIVE

DISADVANTAGES

1) RESULTS ARE AVERAGED ALONG LIGHT PATH

FIGURE 14

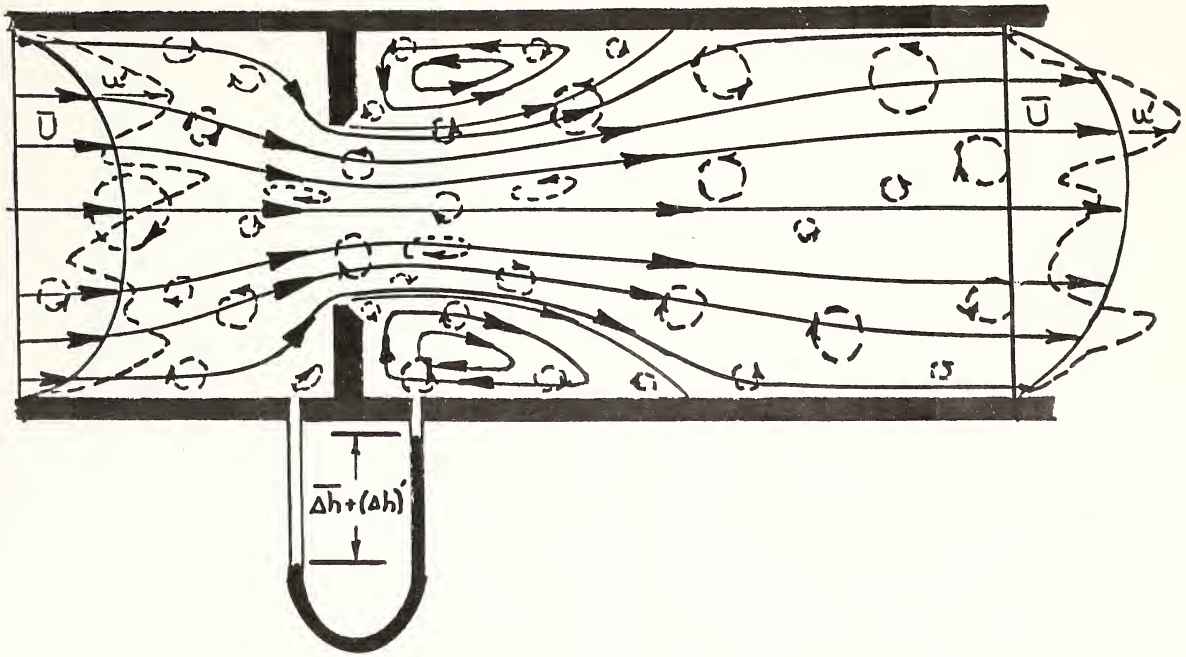


FIGURE 15

Conclusions

We have attempted to show that new research efforts are now needed to produce an understanding of the fundamental fluid dynamic phenomena that control orifice performance. This understanding and how those phenomena controlling meter performance are affected by the parameters involved in practical orifice metering will lead to improved installations as well as improvements in orifice technology. This, in turn will produce the improved levels of measurement accuracy currently demanded by industry. The new experimental research tools needed for these efforts exist and are available. These efforts, in conjunction with collaborative computational counterparts, offer maximal potential to establish the understanding needed. When a collaborative testing program is added, the way to dramatically improve orifice metering practices becomes clear. All that is needed is a commitment by science and industry to pursue the task at hand and to reap the resulting scientific and industrial rewards.

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POTENTIAL ROLE OF COMPUTER MODELING IN ORIFICE RESEARCH

by

K. N. Ghia and U. Ghia
Department of Aerospace Engineering and Applied Mechanics
University of Cincinnati
Cincinnati, Ohio

Introduction

Flow through orifice meter geometries is extremely rich in basic fluid mechanical phenomena produced by the abrupt contraction and expansion of the inlet-pipe-flow, see Fig. 1. The flow converges through the hole in the orifice plate, separates from the lip of this hole and reattaches on the pipe wall at a downstream location dependent on the flow parameters, see Fig. 1(a). The resulting separated shear layer may be steady or unsteady, laminar or turbulent, again, depending on the flow parameters. A weak, elongated, separated-flow region may occur in the corner produced by the inner pipe wall and the upstream surface of the orifice plate, analogous to the observations in similar two-dimensional (2-D) configurations, see Figs. 1(b) and (d). A strong recirculation region occurs behind the orifice plate between the jet flow separated from the tip of this plate and the pipe wall, see Fig. 1(c) and (d). The pressure distribution produced by this flow is sensed by pressure taps placed according to standards at specific locations before and after the orifice plate.

In orifice metering systems, the upstream piping, with its various bends, can induce significant swirl into the pipe flow entering the meter. If not eliminated by fluid diffusion or flow conditioning devices installed for this purpose, this swirl can lead to three-dimensional effects and erroneous measurement of the flow. The actual process of metering in the field can involve the effects of compressibility and turbulence. However, it is advisable to defer the consideration of these two features until the corresponding laminar, incompressible case has been analyzed more fully. Techniques thereby developed can then be applied to analyze more complicated flow features. The simpler case would therefore serve as the starting point for attacking the more complex flows.

Analysis and Numerical Methods

It is our purpose here to introduce the various members of the flow community, from practical metering engineers to those involved in basic, experimental research on fundamental flow phenomena, to the potential power of computer modeling for producing both practical and fundamental understanding of the

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+Some of the research reviewed herein was supported, in part, by AFOSR Grant No. 80-0160 and, in part, by NASA Lewis Grant No. NAG-3-194.

ORIFICE FLOW FEATURES

- THREE-DIMENSIONALITY
- GEOMETRICAL COMPLEXITIES
- RECIRCULATING SECONDARY FLOWS
- STREAMWISE SEPARATION
- UNSTEADINESS
- COMPRESSIBILITY AND TURBULENCE

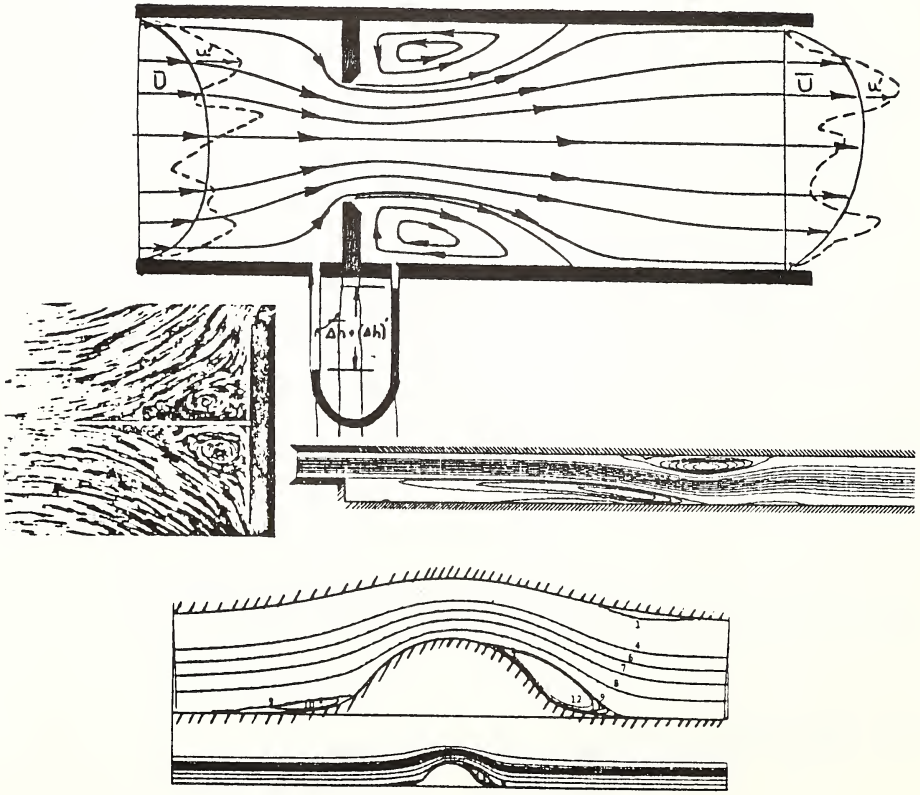


FIGURE 1

fluid flow behavior in orifice plate geometries. To accomplish this, it will be necessary to present some of the philosophical and practical considerations surrounding the development and implementation of currently used numerical modeling schemes. We shall attempt here to do this in such a way as to spare the reader from excessive technical detail.

The success of an analysis of fluid flows depends greatly on its mathematical formulation. This formulation must be sufficiently realistic to yield results which can be expected to apply to the actual laboratory system being modelled yet must be sufficiently simple to be tractable with only the application of reasonable computing facilities. Hence, careful attention must be given to the various elements of the formulation.

In particular, the coordinate system employed should permit accurate implementation of boundary conditions for general geometries which are applicable to the real problem, while also providing grid-point clustering to resolve the various flow features of the problem. Transformed coordinates may, of course, be used. These may be determined from the actual geometrical coordinates of the problem by direct analytical and algebraic techniques as well as by indirect differential-equation procedures.

Choices of the dependent variables must be made (velocity- pressure, velocity-vorticity, vorticity-stream function) as well as the form of the conservation equations to be used. For example, momentum may be conserved along the physical coordinate directions or along the transformed coordinate directions. Both conservation statements can be expressed in terms of transformed coordinates. The transformed equations are discretized in a convenient, generally rectangular, computational domain. Besides allowing the solution of the problem to be determined with a reasonable amount of computing resources, the discretization process must also pay attention both to the consistency of the differencing scheme used and to the associated truncation errors. For example, accurate first-order schemes have large dissipation errors associated with them and tend to smear narrow regions where gradients are large. On the other hand, second-order accurate differencing schemes have dispersion errors associated with them and can result in spatial oscillations in the solution at the edges of high-gradient regions. These oscillations can be eliminated if the grid-point distribution is chosen so as to satisfy the local cell-Reynolds number requirements, see (1,2).

The discretized equations comprise a system of coupled nonlinear algebraic equations which must be solved numerically. Again, consideration must be given to many important factors which make a numerical solution algorithm both versatile and robust. These factors include the manner chosen for treating the coupling and the nonlinearities in the equations, the manner of implementing boundary and initial conditions, and the use of fixed grids as opposed to solution-adaptive grids. In order for the method to be robust, consideration must be given to the use of fully implicit (direct) and semi-implicit (iterative) procedures versus explicit solution techniques. The convergence rate of implicit iterative algorithms can be improved by optimizing iteration parameters. However, it is not practical to determine the optimal values for these parameters for general problems. Significant gains in convergence rate of conventional iterative methods are now achievable

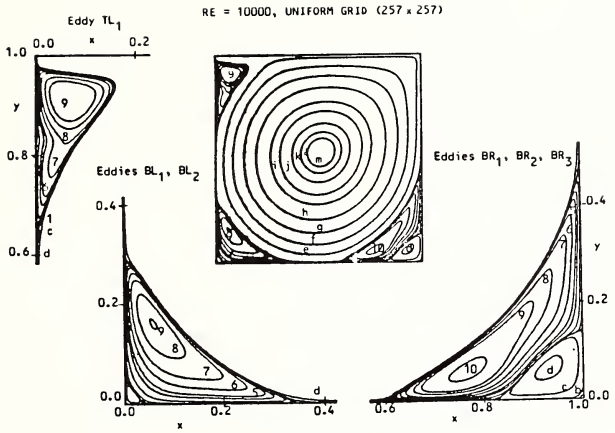
by the use of the recently emerging technique of multi-grid cycling which is frequently insensitive to the iteration parameter values, see (3). On the other hand, explicit procedures are easier to vectorize and can be reasonably efficient on vector computers, but yet may not be competitive with implicit procedures. In the category of direct solution procedures used in conjunction with generalized coordinate systems, block Gaussian elimination constitutes an extremely efficient technique for solution of the stream function equation in a vorticity-stream function formulation or for the Neumann pressure problem in a velocity-pressure formulation for unsteady flow problems, (2).

Illustrative Results

1. Flow in a Driven Cavity

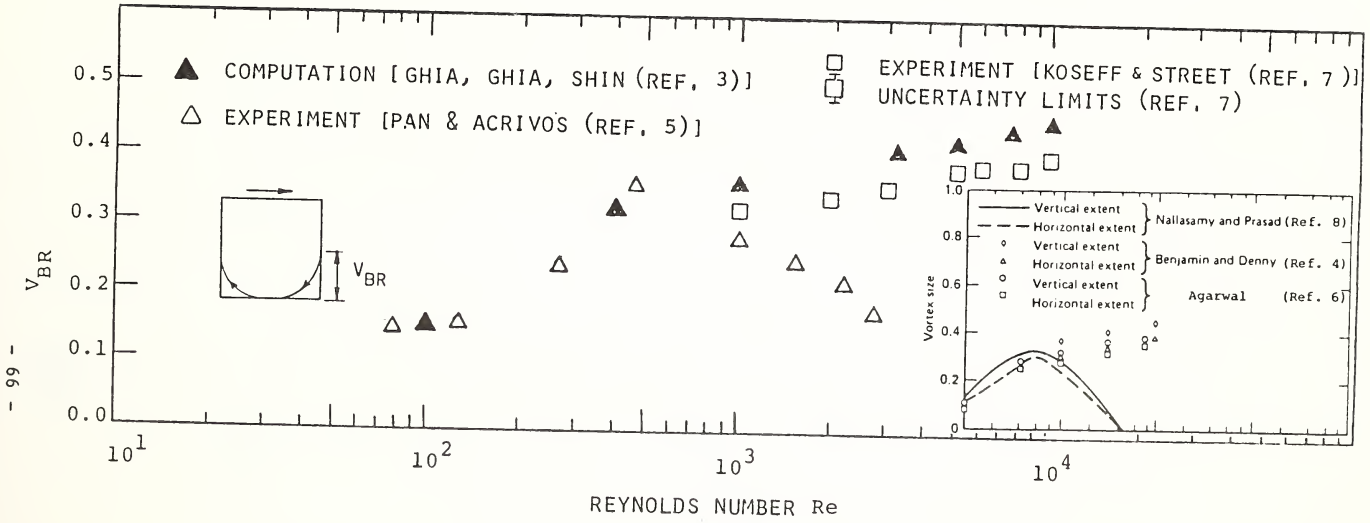
With proper care in the mathematical formulation of a problem and in the implementation of its numerical solution procedures, accurate simulation of physical phenomena in flow devices is now feasible. This is illustrated in Figs. 2-8 for three model problems. The first model problem consists of the flow in a driven square cavity. Until recently, an accurate and most efficient simulation of this problem for Reynolds number Re = 10^4 required approximately 88 minutes of computing time on the IBM 360/91 computer, (4). The present authors' use of multi-grid acceleration reduced the required CPU time by a factor of fourteen, (3). The high grid-point density employed in the calculations enables resolution of a sequence of three secondary eddies (Moffatt corner eddies) in the lower-right corner of the cavity, in addition to the eddies in the lower-left corner and near the upper-left corner, see Fig. 2(a).

For establishing the credibility of the numerical solutions, the computed 2-D results of the vertical extent (depth) of the downstream eddy are compared in Fig. 2(b) with the data of Pan and Acrivos, (5). Their cavity was a cube with both streamwise and spanwise aspect ratios of unity. The present results agreed well with the data up to Re = 400; but, for Re 400, the data show a trend completely opposite of that of the 2-D computed results. The inset of Fig. 2(b) shows the results of two other investigators, (4,6); these agree with our computed results given in (3). A closer examination of all of these results showed that the experimental data is strongly three-dimensional. The results of recent measurements at Stanford University for a cavity with streamwise aspect ratio of 1 but spanwise aspect ratio of 3, (7), follow the computed results, thereby indicating that the spanwise aspect ratio is an important parameter contributing to three-dimensionality in the flow. The two important observations to be noted are that the measurements of (7) are made in a flow which is closer to 2-D flow and that the computations of (8) using an upwind differencing method and a somewhat coarse grid lead to erroneous results. This serves to illustrate that experiments as well as computations should be performed and evaluated carefully and their results interpreted cautiously. By moving back and forth between computation and experiment in such a coordinated interactive approach, it becomes possible to attain an understanding of the prevailing flow phenomena more rapidly and to improve both the computer model and the experimental investigation.



STREAMLINE PATTERN FOR PRIMARY, SECONDARY AND ADDITIONAL CORNER VORTICES IN SHEAR-DRIVEN CAVITY FLOW, Re = 10000 (REF. 3).

FIGURE 2(A)



VERTICAL EXTENT OF SECONDARY DOWNSTREAM EDDY - COMPARISON BETWEEN COMPUTATIONS AND MEASUREMENTS.

FIGURE 2(B)

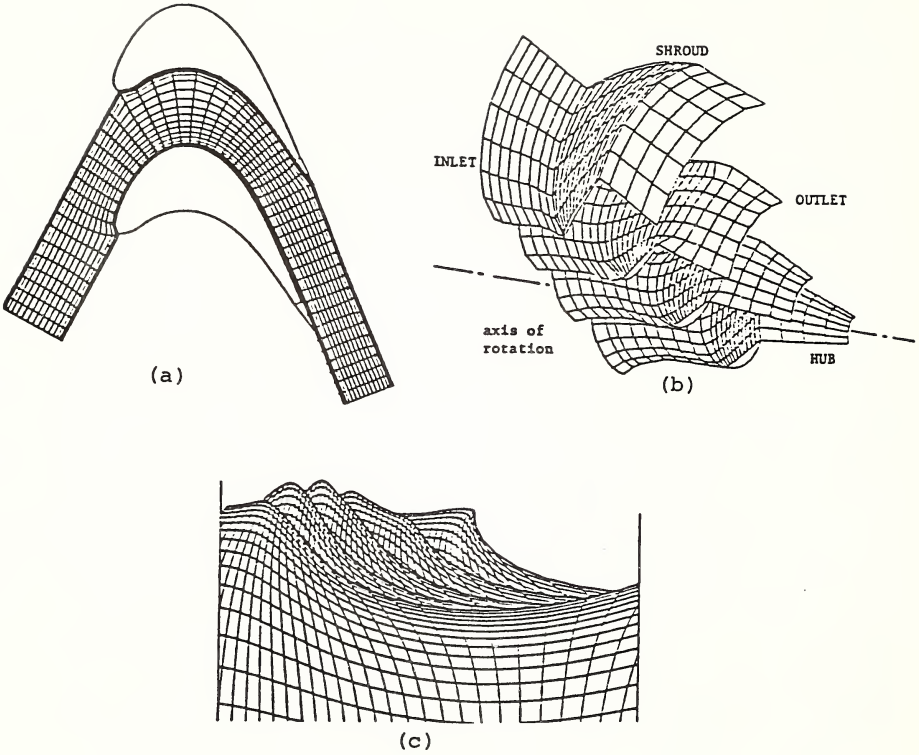
2. General Coordinate Transformations

The model problem of flow in a driven-cavity was relatively simple geometrically and, hence, was represented simply in Cartesian coordinates. For general complex configurations, techniques are now available for generating boundary-oriented coordinates, as illustrated in Fig. 3. In the transformed plane, the coordinates are rectangular, uniformly spaced and time-independent, making the discretization of the flow equations and the associated computer program simple. In the physical plane, the coordinates are curved to accommodate general geometries, non-uniformly spaced for accurate resolution of local scales in the regions where the flow variables vary rapidly. They may also be time-dependent (as in free-surface problems) to accommodate temporally varying boundary shapes. It is, in this way, possible to treat very complicated geometries, (9). The coordinate transformation can be made solution-adaptive to accommodate changing features in the flow, (1). These concepts should be very useful in analyzing more complex orifice flows, e.g. those in which the orifice plate has a rounded lip and for which deflections of the plate are non-negligible, (10).

3. Flow in a Constricted Channel

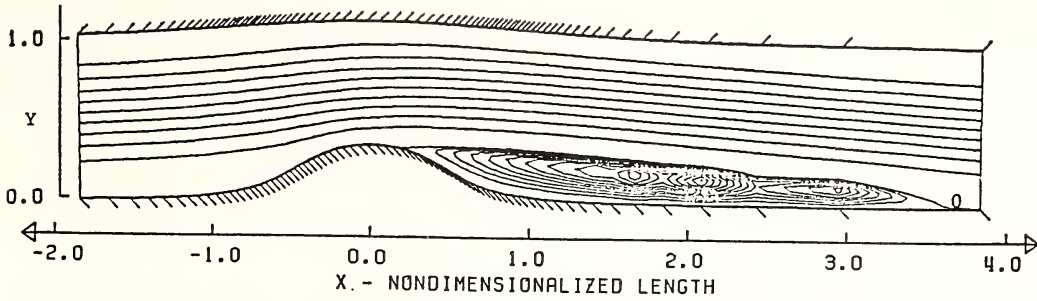
The use of appropriate coordinate and grid-point distributions plays a significant role in the accuracy of the numerical predictions by honoring the various scales of the flow problem properly. This is vividly demonstrated in the second model problem, namely, a channel with an asymmetric constriction, see Fig. 4. Inadequate resolution of the reattachment region near the lower wall leads to an erroneous picture of the steady-state solution consisting of four co-rotating secondary bubbles within a primary separation bubble, see Fig. 4(a). This type of behavior is generally characteristic of unsteady flow, and, as it turns out, it gives a totally erroneous picture of the steady flow. The true solution consists of a single separation bubble as shown in Fig. 4(b) obtained with improved grid-point distribution.

From the detailed flow-field results obtained for the asymmetric channel, see (11), an attempt has been made to ascertain the extent of the upstream and downstream influences of the channel constriction for the various configurations studied in (11). This analysis is possible since the geometry considered is a doubly infinite channel in which the correct boundary conditions are placed at true upstream and downstream infinity. Often in engineering applications, these boundaries are placed at finite distances from the constriction. In these situations, the present results given in Table 1 should aid in arriving at appropriate locations for the placement of the inflow and outflow boundaries. The predicted results are in agreement with the asymptotic analysis of Smith, see (12). These results should be of significance in orifice metering where it is necessary to determine the effects of different upstream lengths of straight pipe, i.e., installation

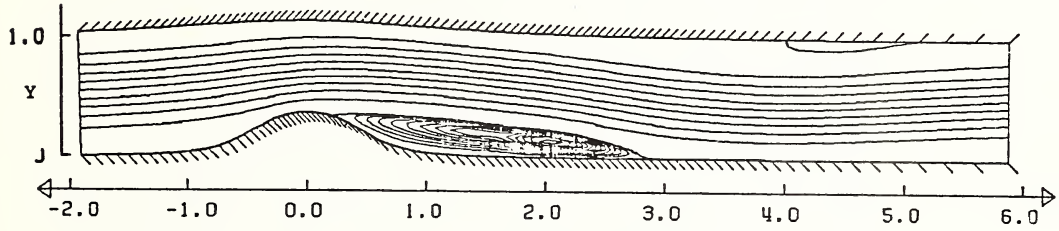


BOUNDARY-ORIENTED COORDINATES FOR ARBITRARY COMPLEX GEOMETRIES.
(a) BLADE-TO-BLADE SURFACE OF CASCADE WITH ZERO TWIST.
(b) BLADE-TO-BLADE SURFACE OF GENERAL ANNULAR CASCADE (REF. 19).
(c) TEMPORALLY DEFORMING FREE-SURFACE WAVE (REF. 20).

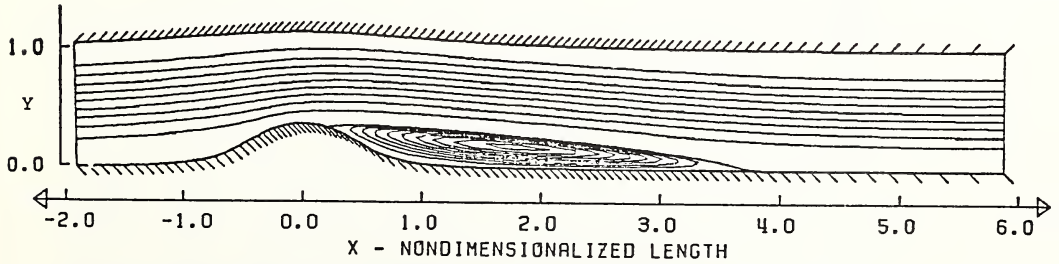
FIGURE 3



(a) STEADY-STATE SOLUTION (AT T = 45) WITH INAPPROPRIATE MESH.



b(i) TRANSIENT SOLUTION (AT T = 8) WITH IMPROVED MESH.



b(ii) STEADY-STATE SOLUTION (AT T = 41) WITH IMPROVED MESH.

STREAM-FUNCTION CONTOURS FOR CONSTRICTED CHANNEL FLOW.
Re = 1000, $\Delta\psi = 0.002$ WITHIN SEPARATION BUBBLE;
$\Delta\psi = 0.1$ OTHERWISE.

FIGURE 4

TABLE 1. RANGE OF UPSTREAM AND DOWNSTREAM INFLUENCE DUE TO CONSTRICTION FOR TWO ASYMMETRIC CHANNEL CONFIGURATIONS.

Configuration*	Re	Property	Upstream Distances†			Downstream Distances†	
			Departure From Parabolic Profile		Smith's Asymptotic Analysis	Departure From Parabolic Profile	
			1%	5%		1%	5%
I	100	ψ	4.47	2.49	O (2.75)	3.09	2.62
		ω	7.84	3.62		7.48	4.14
II	100	ψ	6.25	3.72	O (2.75)	7.26	3.45
		ω	12.50	5.70		10.43	5.98
I	1000	ψ	7.71	4.57	O (3.83)	31.60	16.59
		ω	9.83	5.24		38.99	17.75

* Configuration I: $a^2 = 0.210$, $h = 0.782$

Configuration II: $a^2 = 0.585$, $h = 0.678$

† Nondimensional distances measured from point of maximum constriction.

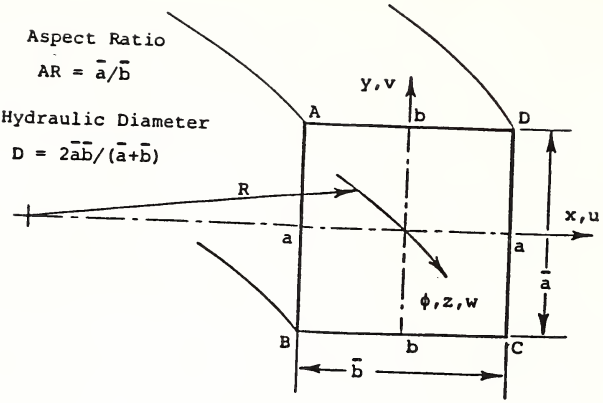
criteria. Further, any bends in the piping upstream of the orifice metering system can lead to additional complexities in the flow. For non-circular bends, K. Ghia, U. Ghia and Shin, (13), have shown that the structure of the 3-D flow is made very complex due to the appearance of additional streamwise vortices as shown in Fig. 5. Similarly, circular bends also exhibit the possibility of such an additional pair of streamwise vortices, but additional experiments are required to verify this phenomenon of Dean's instability for circular bends. In any case, the presence of even the first pair of streamwise vortices will make the upstream flow three dimensional and its influence on the orifice metering may be significant.

4. Flow in a Channel With a Backstep

The final example discussed here is the flow through a doubly infinite channel with a backstep. For laminar flow, K. Ghia, Osswald and U. Ghia, see (2), solved the unsteady Navier-Stokes equations to determine the detailed flow results. As shown in Fig. 6, the important parameter, namely, the primary separation bubble reattachment length, compared favorably with the experimental data of Armaly and Durst, (14), up to $Re_s = 212$, where Re_s is the Reynolds number based on the step height. Thereafter, there is a significant discrepancy in the two sets of results. A closer examination of the backstep configuration revealed that, at $Re_s = 212$, the computation showed the formation of a secondary separation bubble. In the experiment, three-dimensional effects are involved and generate a significant spanwise variation. Hence, the differences observed in Fig. 6a are due to the effect of three-dimensionality on the flow. Osswald, K. Ghia and U. Ghia, have recently computed the unsteady flow for this configuration at Re = 2000, see (15). This configuration is well within the transition regime and the predicted flow does not exhibit a steady state. Examination of the results in Fig. 7 between T = 117.8 and T = 120.4 shows a near-limit-cycle behavior associated with the generation, downstream convection and eventual dissipation of large-scale coherent vortex structures. This is an example of self-sustaining oscillatory motion where disturbance mechanisms are developed without any external excitation. Figure 7 shows a typical shedding cycle associated with the primary recirculation zone. Due to vortex shedding, the flow in the zone downstream of the primary reattachment point is very unsteady. The time-averaged stream function and vorticity contours are presented in Fig. 8. Three separation bubbles persist in time-averaged flow as seen in Fig. 8a. The present unsteady Navier-Stokes analysis is capable of computing many of the features characteristic of turbulent-flow. The complete knowledge of the instantaneous motion as well as the mean motion can make it possible to determine statistical information about the flow.

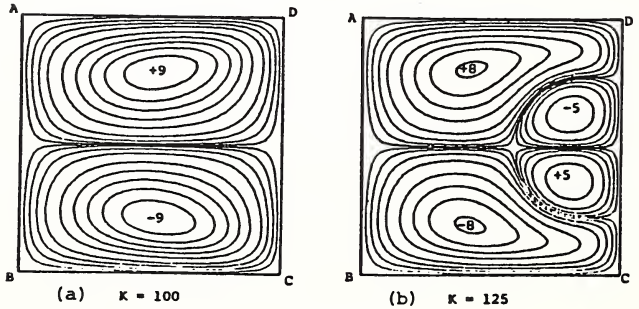
CONCLUSION

In summary, it should first be pointed out that both laminar and turbulent incompressible flows in orifices have been studied numerically by researchers for over 15 years. The available tools of numerical analysis of the last decade are well represented in the works of Mattingly and Davis, (16), and Davis and Mattingly, (17), on laminar and turbulent flows, respectively. However, in the last few years, significant progress has been made in the accuracy and efficiency of basic numerical calculations, as we have illustrated in this paper with the help of model problems. If additional



Reynolds Number, $Re = \frac{w_{avg} D}{\nu}$

Dean Number, $K = Re/\sqrt{R}$

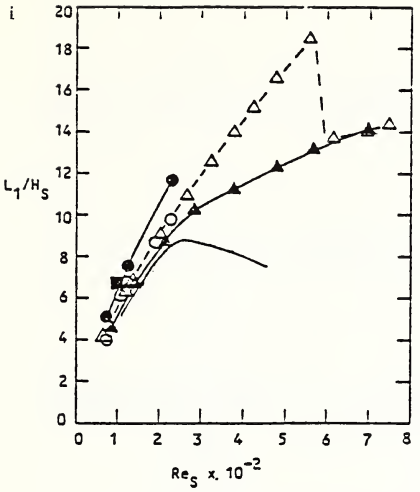


SECONDARY-FLOW STREAMLINES IN CURVED SQUARE DUCTS.

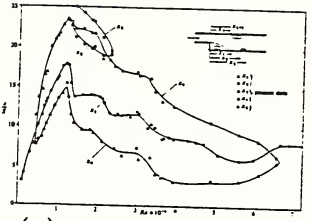
(a) TWO STREAMWISE VORTICES AT K = 100.

(b) FOUR STREAMWISE VORTICES AT K = 125, FOLLOWING DEAN'S INSTABILITY.

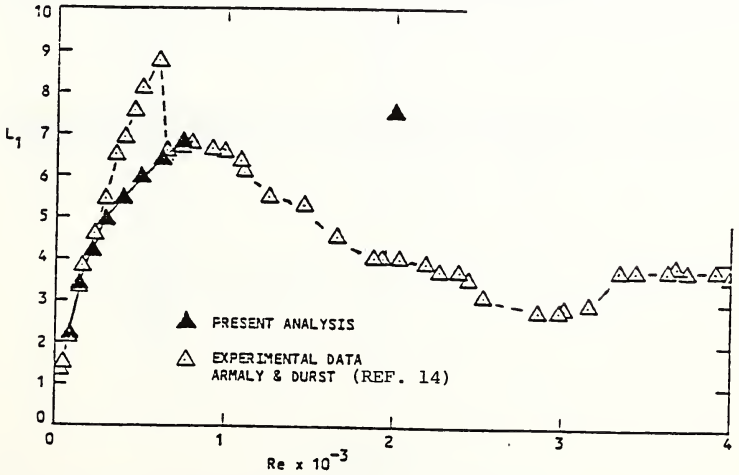
FIGURE 5



(A) SIMILARITY STUDY OF PRIMARY REATTACHMENT LENGTH.

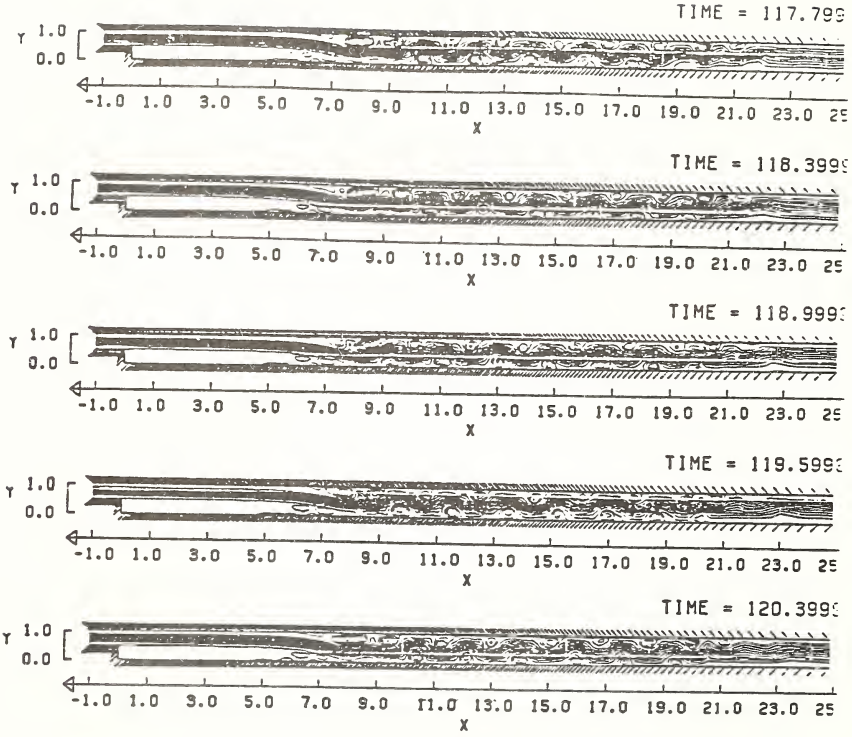


(B) SEPARATION AND REATTACHMENT LENGTHS AFTER REF. 14



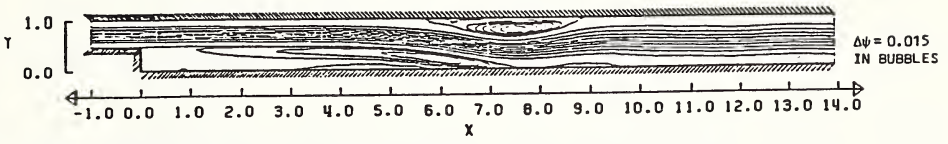
(C) COMPARISON OF PRIMARY REATTACHMENT LENGTH IN TRANSITION REGIME.

FIGURE 6

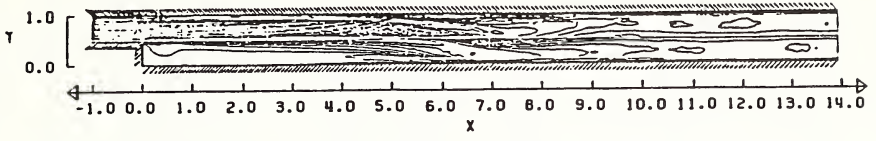


STREAM-FUNCTION CONTOURS FOR UNSTEADY FLOW IN TRANSITION REGIME; Re = 2000, $\Delta\psi$ = 0.1 FOR MAIN FLOW; $\Delta\psi$ = 0.0536 IN BUBBLES.

FIGURE 7



(A) TIME-AVERAGED STREAM-FUNCTION CONTOURS FOR $95.02 \leq T \leq 117.00$;
Re = 2000, $\Delta\psi = 0.1$.



(B) TIME-AVERAGED VORTICITY CONTOURS FOR $95.02 \leq T \leq 117.00$;
Re = 2000, $\Delta\omega = 2.0$.

FIGURE 8

improvement in the accuracy of orifice flow computations is desired, studies such as these which incorporate recent progress should be carried out.

It should be emphasized that the computer modeling of orifice flows must be done in concert with a well developed and well coordinated experimental measurements program. This will be of particular importance in the fully turbulent flow regime. Indeed, it is this combined effort that will permit the realization, in a reasonable time and within a reasonable budget, of the goal of improving orifice performance through an improved understanding of the characteristics of orifice flow. The cost of such a total program should be viewed from the perspective of the potential gains that may be realized. Further, although the costs of experimental measurements is increasing regularly, the cost of numerical computation is decreasing, so that the overall cost of a combined numerical-experimental orifice research program should not increase significantly in time.

A computer code, well validated by comparison with accurate experimental measurement, can now be developed to provide the essential tool for a parametric study to evaluate the sensitivity of orifice performance to the following effects:

- upstream pipe flow conditions
- upstream flow disturbances
- length of requirements for straight pipe between an orifice plate and any upstream sources of disturbance
- the departure from the concentric placement of orifice plates in the pipe
- the beveling or the rounding of the edges of orifice plates
- the bending of an orifice plate due to the pressure differential across it.

It should also be recognized that in a computational fluid dynamics analysis of orifice flow, the prevailing fluid dynamics phenomena must be emphasized first, followed by a careful study of its computational aspects. Laser Doppler velocimetry can go a long way towards this goal as this measurement technique provides a detailed quantitative time history of the flow.

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GAS ORIFICE METER TESTING AT NBS-BOULDER

by

J. A. Brennan
National Bureau of Standards
Boulder, CO

Introduction

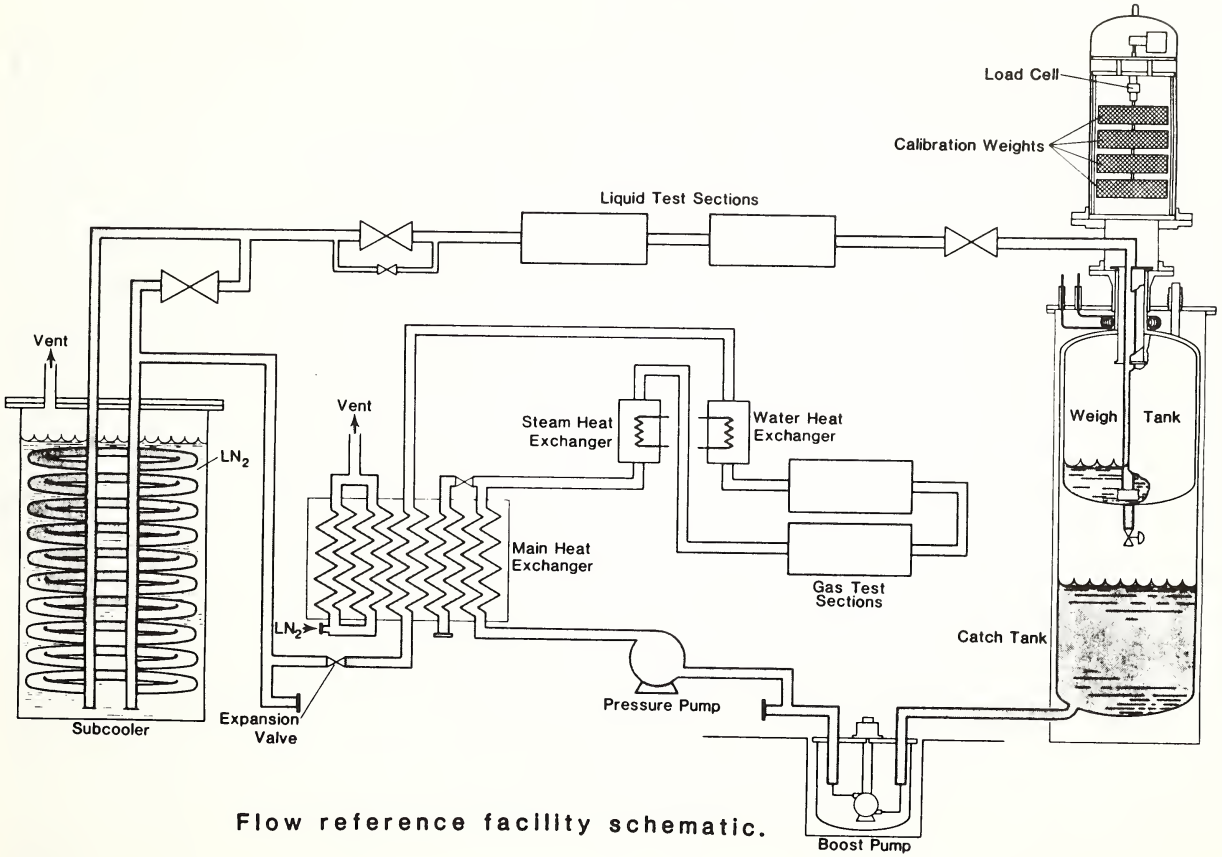
Staff members of the National Bureau of Standards (NBS) laboratories located at Boulder, Colorado (USA) have modified an existing cryogenic liquid flowmetering facility to allow the precise measurement of the rate of flow of gas through a flowmeter at ambient temperatures. In the approach used, the gas meter measurement is compared directly to a liquid mass flow reference system which is based on very accurate mass and time measurements (1). An extensive program of research on gas flowmetering based on this new facility is in progress. The program was initially supported jointly by the American Gas Association (AGA) and the Gas Research Institute (GRI) and is currently funded entirely by GRI. The cryogenic liquid measurement part of the program continues under sponsorship of the Compressed Gas Association (CGA). The research is coordinated by an advisory committee and a program manager at GRI.

The committee provided NBS-Boulder with two sets of orifice meter runs in four nominal line sizes (5.1 to 15.3 centimeters diameter) with orifice plates which provided six beta ratios ranging from 0.2 to 0.75 for each run size. In a collaborative effort, some of the same meter runs and orifice plates will be tested at NBS-Boulder (with gas), at NBS-Gaithersburg (with water) and at the Joliet metering facility of the National Gas Pipeline Company (with natural gas). The orifice meter runs, plates and flow conditioners were fabricated to natural gas industry (U.S.) standards and are the joint property of AGA and the American Petroleum Institute (API). Using these multiple sets of runs and plates, a more representative range of meter performances can be studied as compared to that possible for a single run size using only one or two special orifice plates. The performance of several of these combinations is reported here. A more extensive report has now been published (2).

Data presented provide added confirmation that gas orifice metering performance anomalies, which were suspected, do exist in the flow range covered. The data do not, however, necessarily reveal the sources of these anomalies. Research is continuing in order to try to establish a rational basis for designing a measurement program for producing the added data needed to improve significantly or to replace present correlations.

Reference Flow System

The flow reference system is shown schematically in Fig. 1 and consists of a closed loop thermodynamic cycle where the process fluid, nitrogen, is circulated between temperature limits of 85 K and 300 K at pressures of 0.5 MPa to 4.1 MPa. The gas flowmeters being tested are installed in the gas test section. Flow is initiated and maintained by the boost and pressure pumps. The fixed operating pressure, temperature and flow rate at the gas meter is controlled by the operation of the expansion valve and the steam heat exchanger. After a steady state has been established, the valve in the weigh tank is closed and the test draft period is started. During this period the



Flow reference facility schematic.

FIGURE 1

flowmeter and system pressure and temperature transducers are read and recorded at about 1 second intervals with great care being taken to maintain stable conditions. The entire flow system measurement process, and the data acquisition are computer controlled. At the conclusion of the test draft period the load cell records the mass of the test draft, the weigh tank valve is opened and a new flow rate is established. The test draft and data recording period are repeated. The flow rates are varied in a random test sequence with six to twelve flow rates (several repeat points) measured over the applicable gas meter flow range and within the reference system flow range of 0.45 to 2.5 kg/s.

Orifice Flowmeter Tests

Tests were conducted on both sets of the four sizes of meter runs. These pairs of meter runs which are identified as FE 1 and FE 2, FE 3 and FE 4, etc., are of the same nominal size. Orifice plates identified as 1A and 1B, 2A and 2B, etc. are in sets of the same nominal orifice size. The orifice plate pressure differential was limited to the range of 2.5 to 49.8 kPa which, along with the flow range limitations of the flow facility, precluded testing all orifice plates. Table 1 indicates which orifice plate-meter run combinations were tested in this phase of the program. As can be seen in the table, it was not possible to test a complete set of orifice plates in any line size.

Table 1 Orifice Plate-Meter Run Test Combinations.

Run/Orifice	1A	1B	2A	2B	3A	3B	4A	4B	5A	5B	6A	6B
FE 1							X	X	X	X	X	X
FE 2							X	X	X	X		
FE 3			X	X		X		X	X	X		X
FE 4			X	X	X	X	X	X	X	X	X	X
FE 5			X	X	X	X	X	X	X	X	X	X
FE 6			X	X	X	X	X	X	X	X	X	X
FE 7	X	X	X	X	X	X	X	X				
FE 8	X	X	X		X	X	X	X				

The test plan used in this study was randomized in flow rate, plate selection and run selection. A series of randomized flow rate tests were conducted for each orifice plate-meter run combination. The method of taking data with continuously increasing or decreasing flow rates was not used. Repeat flow rate points were also randomized. With one exception, repeat tests with a given orifice plate were not done without at least removing and replacing the plate. Normally, repeat plate tests were not done consecutively.

Orifice Meter Performance

The data were analyzed by calculating the product of the discharge coefficient, C, and the expansion factor, Y2, and plotting the results as a function of the Reynolds number. It was not possible to separate the values of C and Y2 in this phase of the program although tests are now under way which will allow this to be done by measuring the flow rate of the fluid in the liquid state. This product was calculated using equation (1).

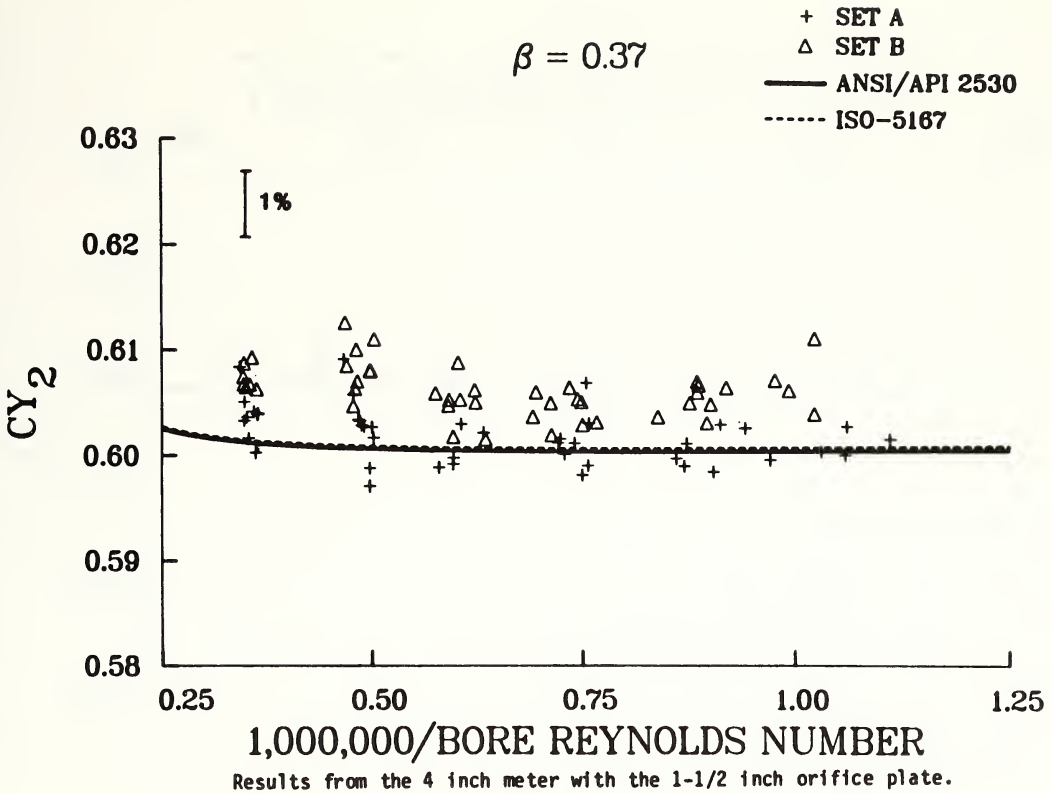
$$CY2 = (\text{constant})\ (\dot{M})\ (1-\beta^4)^{1/2}$$

$$(F_a)\ (d^2)\ (\rho\ \Delta P)^{1/2}$$

Where C = discharge coefficient.
$Y2$ = expansion factor based on downstream pressure.
$\dot{M}$ = mass flow rate.
d = diameter ratio or beta.
F_a = orifice plate thermal correction factor.
ρ = gas density.
ΔP = orifice differential pressure.
constant = numerical function of dimensions and conversion factors.

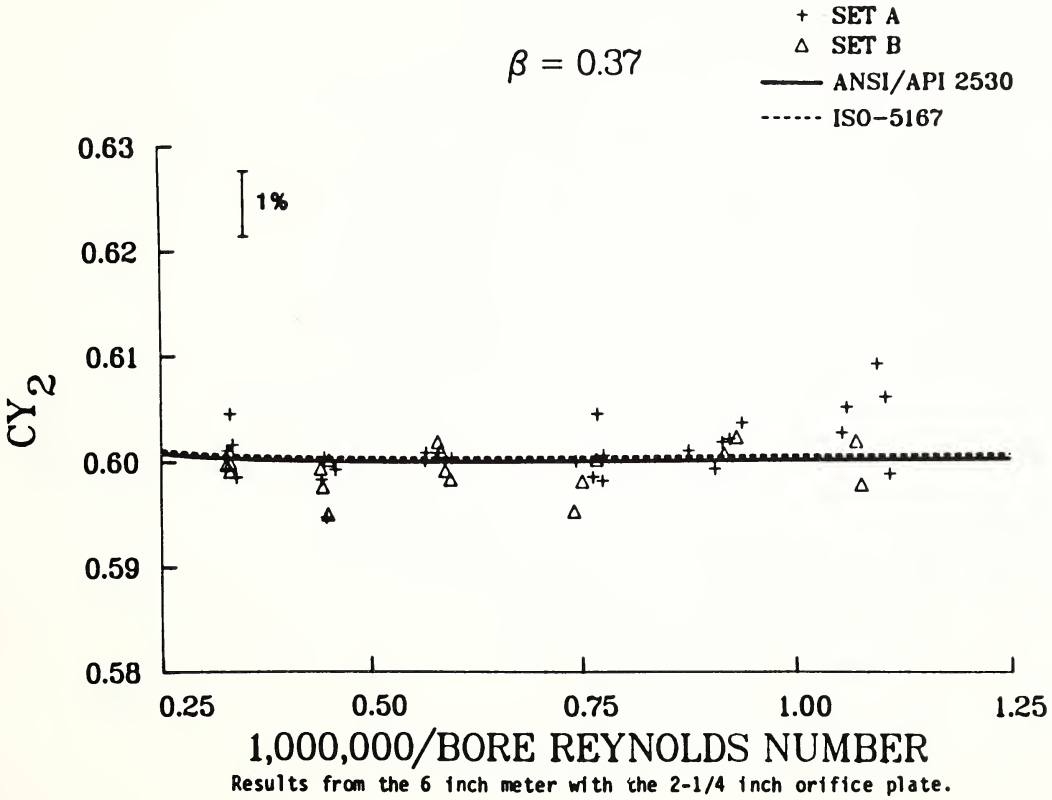
Figures 2 and 3 show some typical results for two different line sizes. Also included on the figures are the calculated CY2 values obtained from the two most commonly used equations. The dotted line represents the values calculated using the equations of ANSI/API 2530 (3) and the dashed line represents values calculated using the equations of ISO 5167 (4). Expansion factors, Y2, were calculated using the equations from (3).

All the data are plotted as a function of the reciprocal bore Reynolds number. Set A and set B refer to the two sets of orifice plates at each beta ratio.



Results from the 4 inch meter with the 1-1/2 inch orifice plate.

FIGURE 2



Results from the 6 inch meter with the 2-1/4 inch orifice plate.

FIGURE 3

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3. American National Standards Institute, ANSI/API 2530, "Orifice Metering Of Natural Gas", American Gas Association, 1515 Wilson Boulevard, Arlington, VA 22209, 1978.

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THE EEC ORIFICE COEFFICIENT PROGRAM

by

E. A. Spencer
National Engineering Laboratory
East Kilibride, Scotland

Introduction

An extensive program of tests to determine orifice plate coefficients more accurately is being carried out under the aegis of the Directorate General for Science, Research and Development of the Commission of the European Economic Community (EEC). The Commission is funding half the cost of the program and the seven organizations involved in carrying out the tests are funding the other half. Each organization is, in fact, contributing additional resources by undertaking associated programs to resolve other aspects of the total problem. This makes it difficult, if not impossible, to estimate the true cost of the entire program; a conservative estimate would indicate that not less than half a million dollars of effort have already gone into the project. The program has, to date, produced several thousand test points.

The author is Chairman of the Experts Group which is responsible for the technical planning and assessment of the project on behalf of the Commission. The Group is made up of representatives both from the organizations carrying out the various test programs on flow measurement of gases in the EEC DGX11 Applied Metrology Program and from the Legal Weights and Measures Departments of the EEC countries participating.

The organizations involved in the Orifice Coefficient Project testing are:

in The Netherlands, NV Ned. Gasunie and the Delft Hydraulics Laboratory,

in France, Gaz de France and CEAT at the University of Poitiers,

in Western Germany, Ruhrgas, and

in Great Britain, the British Gas Corporation and the National Engineering Laboratory.

Among these seven organizations is a substantial number of test facilities, several of which are suitable for use on this project. Of these, two test facilities using water as the working fluid, two using compressed air and four using natural gas are being utilized. It has been said - "never put two orifice plates in series unless you want an argument about the flow-rate they are measuring?". It will therefore be asked: "Why then is the EEC programme using eight test facilities to carry out this programme? There are bound to be eight different sets of answers and it will be impossible to tell which one is right".

In fact, this use of many facilities was a very deliberate policy decision by the EEC Group. It has already proven useful in providing vital information obtainable from the data being accumulated at these different laboratories. The statisticians state that every measurement must have some systematic bias which cannot be removed, no matter how many more tests are made using the same arrangement of instruments at the same test facility. It is only possible to reduce such systematic bias by using different and independent facilities to carry out the tests. With eight facilities involved there is, then, an excellent chance of ultimately obtaining an answer closer to the truth.

Traceability of test facilities

Before the orifice coefficient program began, the Experts Group undertook a three-year exercise, also under the EEC Commission's aegis and support, to carry out an intercomparison of the primary high pressure gas test facilities in the EEC. At that time, only three such facilities were available: the gravimetric 60-bar facility at NEL, the volumetric facility at the Gaz de France experimental station at Alfortville, and that belonging to Gasunie at Groningen. The latter was linked to the low-pressure primary test facility at the Weights and Measures Service at Dordrecht through a battery of turbine meters separately calibrated. Eight transfer standards, six of them sonic nozzles, were used in the intercomparison, each being tested in the three facilities. The results of the work, which showed an overall agreement to within 0.3%, are fully described in an EEC Publication obtainable from the Commission in Brussels (1).

In addition to this joint exercise which was directly under the aegis of the Commission, a number of individual intercomparisons were undertaken between pairs of organizations. Thus there was one between NEL and DHL at Delft in The Netherlands, recently published by NEL as a joint NEL/DHL Report (2). Gasunie and Ruhrgas and Ruhrgas and DHL were among the other pairings. Results of these efforts will eventually be published. So it is that there now exists a network of cross-traceabilities among these various facilities and others all of which are ultimately linked to each of their country's own primary standards of length, mass, time, etc.

EEC Orifice Plate Project

Let us now return to the main subject of this report, the EEC Orifice Plate Project. The Experts Group at an early stage in the program, concluded that it would be important to relate the work to that in progress in the USA jointly sponsored originally by AGA and API and currently being funded by GRI and API. It was originally considered that the US and EEC programs might be combined into one overall project. It soon became apparent, however, that it would require an inordinate amount of time to complete such an effort. A separate, but closely allied, plan was therefore agreed upon within the EEC Experts Group. To ensure the greatest amount of integration, Daniel Industries (UK) Ltd. was asked to manufacture a 4-inch meter run which was essentially a facsimile of the 4-inch run now being used in the AGA and API tests at the NBS at Boulder and Gaithersburg, respectively. In addition, Gasunie was asked to commission the manufacture, in the Netherlands, of a 10-inch meter run which would also be similar to the one designed by Daniel Industries Ltd. in Houston for the GRI/API Project.

The objective of the EEC Project was "to determine the discharge coefficients of orifice plates used to calculate the flow in pipelines and to determine the effect of the testing conditions and in particular the parameters which are characteristics of the geometry".

A full description of all the various phases and tests to be covered by the project would occupy many pages. However, it is possible to give here a detailed indication of the scope of the project. The same beta ratios for the orifice plates were chosen as in the GRI/API Program, namely: 0.20, 0.375, 0.50, 0.57, 0.66, 0.75. As indicated above, there are two pipe sizes, one 4-inch and one 10-inch diameter, each manufactured by a different company, but each manufacturer well experienced in making pressure difference devices. Two complete sets of plates were made for each size to make a grand total of 24 plates.

Scope of EEC Project

There were three major planned differences between the program being carried out in the USA and that in progress in Western Europe. These differences are described in some detail.

Pressure Tappings

First, it was considered vitally important by the EEC Experts Group that the design should not be limited to one location for pressure tappings as in the GRI/API project, which was restricted to flange taps. For the EEC meter runs, corner, D and D/2 tappings were also drilled and, subsequently, another set of tappings was made which will be described below. To ensure that the existence of one set of taps did not affect measurements at another, a series of separate calibrations were carried out at NEL. These were done with only flange and corner tappings open and then with the D and D/2 tappings also opened. Except for one case, agreement was well within 0.2% and there was no systematic bias. It should be remembered that this agreement takes into account not only all the measurements required to calculate the flow through the orifice plate but also those required to determine the flow measured by the laboratory's diverter/ weighbridge system.

Gasunie has tested different methods of making tappings for the 10-inch size from the conventional round hole to a special rectangular slot. The 4-inch size meter run also allows for the flange tapping diameters to be increased above the ISO 5167 maximum value but still remain within the AGA Report No. 3 specifications.

In addition to the corner, flange, D and D/2 tappings, a supplementary set of tappings are to be used in the program at a later date. These tappings, which were referred to above, are meant to enable the Group to obtain data which can introduce, in effect, extra sizes of meter runs. Nature does not deal with absolute dimensions in inches or millimeters, but rather deals with relative dimensions. Each area of science has its own set of reducing functions for producing the dimensionless variable on which to base such relative dimensions. In the orifice meter, certain lengths can be reduced relative to

the pipe diameter. Thus, flange taps 2 inches upstream and downstream in a 4-inch pipe have the same non-dimensional effect as the 1-inch locations in a 2-inch pipe. Similarly 1/2-inch spacings in a 4-inch pipeline are the same as 1-inch ones in an 8-inch pipe. Extra tappings have therefore been located at these 2-inch and 1/2-inch positions upstream and downstream of the orifice plate position. When these tappings are opened at a later time, it will be possible to obtain coefficients which can simulate 2, 4, 8 and 5, 10, and 20 inch pipeline flange taps. This will provide a very effective assessment of the sources of the differences in the flange tap data obtained in the earlier US programs. This concept was proposed by J. Stolz during his development of the equations which were adopted for ISO 5167.

Various fluids and facilities

Another difference between the EEC Project and the original API/AGA program has to do with the use of multiple working fluids. This was a natural sequel of the Group's experience with the use of orifice meter runs for different fluids in the various facilities belonging to their organizations.

It is the Group's belief that it is necessary to obtain the widest variety of data in order to obtain the best values for the constants in the Stolz equation as input to the revised ISO standard. Answers so obtained can be expected to lie closest to the truth. If all the work is carried out on one manufacturer's device - in one location - using one set of instruments - one set of physical data measurements - one set of test engineers - and so on, results will be obtained which are not representative of what actually takes place in practice. Carrying out the EEC test program in different places using different staff and facilities should lead to final estimates of uncertainties and tolerances which will much more truly represent what the best user of the standard would obtain when he follows the revised standard.

Installation disturbance tests

Another difference between the EEC and GRI/API tests has to do with special design features of the EEC program to allow for installation disturbance tests. The Experts Group deliberately specified that the upstream length for each of the two meter runs should be made up of a number of spool pieces of different lengths. All were taken from the same run of pipe and the design of the flanges, bolt holes, etc. was such that the location of the spool pieces was exact and repeatable. The first two lengths immediately upstream of the plate, however, were even more carefully matched so that they could be spigotted and bolted together without any measurable steps: these have been kept as a single unit throughout all the primary coefficient calibrations.

This plan was adopted so that a series of installation disturbance tests could be carried out by the various participating organizations. The most serious difference of opinion which exists between those who support ISO 5167 and those who support AGA 3 deals with lengths of straight upstream pipe sections. Thus, AGA 3 indicates high accuracies for very much shorter upstream lengths than are permitted in ISO 5167. The first spool piece length immediately upstream of the plate was therefore made to the AGA length while the second spool piece was spigotted to ensure that, compatible with ISO 5167, a length of 9D is present which can be safely regarded as having no step at all.

Each of the EEC participating organizations has agreed to tackle one of the installation problems. Thus, NEL is testing with two bends at right angles at different distances from the orifice plate. These distances are those given in ISO 5167 and AGA 3. Tests will also be done using an intermediate distance if it is found that there is a discrepancy between the two "standard" locations. Gaz de France is performing similar tests for bends in the same plane; Ruhrgas is testing a header configuration; Gasunie is testing straighteners and so on.

Present position

Several thousand determinations of discharge coefficients have already been obtained for a very wide range of situations. The program is, in fact, approximately half completed and a comprehensive assessment of the results is presently being made. Thus, when the two meter runs pass to the remaining organizations' test facilities, tests can be carried out for various aspects which now, more than three years after the start, are considered to be especially important for inclusion in the program. In addition, as a result of the experience gained to date, it may be necessary to increase the test constraints.

It has been found, as is true in almost every experiment, that some of the results obtained have been erratic. A careful examination of such data has shown that in nearly every such instance the cause of the discrepancy can be identified. This does not mean, however, that similar erratic behavior will not be observed in real situations in a custody transfer pipeline where the true flow is not known. It is believed, however, that as a result of the experience gained in this project it will be possible to give better guidance as to how to avoid such anomalies. It has also been found that in some instances factors were omitted in the calculations which were thought to be insignificant but which, in fact, turned out to be important.

Indications at this time, which is just prior to a meeting of the EEC Experts Group at the Commission's Headquarters in Brussels to discuss these re-assessments, are that, with the more rigorous computations now being applied to all sources of the data, the majority of the results from the various laboratories will be in excellent agreement. It is anticipated that, at the rate of progress now being made, it will be possible to complete the remaining series of tests at the various laboratories within a year. Thus, it can be anticipated that a preliminary report, dealing with the many facets of the work, will be published in 1984, with a full report available perhaps a year later.

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NBS-NEL ORIFICE CROSS-CHECK* TESTING PROGRAM

G. E. Mattingly
National Bureau of Standards
Gaithersburg, MD

Introduction

Interlaboratory testing programs of proven transfer standards enable participants to assess systematic errors that may exist in their individual measurement processes, see (1,2). To carry out such programs in flow measurement requires that a range of specific selections be made regarding the details of the tests and the kinds of laboratory measurement processes that are to be checked. Central among these are the size of the metering transfer standards, the ranges of the flowrates, the fluid to be used, and the fluid state, i.e. its temperature, pressure, etc. Selecting a particular kind of flowmeter will check the capabilities of the participating laboratories to test this type of meter. The types of meters and ranges of flowrate measurements usually made in the respective laboratories generally determines these selections in order that the results of the crosscheck should typify normal performance. Because of the past, current, and expected long-term future interests in using orifice meters for flow measurements for the custody transfer of valuable fluids such as natural gas, an interlaboratory testing program was designed to be carried out involving the National Bureau of Standards (NBS) at Gaithersburg, MD and the National Engineering Laboratory (NEL) at East Kilbride in Glasgow, Scotland, UK. In this way, a cross-link is expected to be generated through the respective orifice meter testing programs being carried out or planned in both the U.S. and the European Economic Community (EEC) countries. Thus orifice measurements in each laboratory can be related.

Selected parameters for this NBS-NEL orifice cross-check testing program are as follows:

type of meter:	orifice, with exchangeable plates having orifice hole to pipe diameter ratios of 0.5 and 0.7
test fluid:	water
pipe diameter:	4 in (10cm) nominal
flowrate range:	$1.5 \times 10^5 \leq Re_D \leq 3.5 \times 10^5$, Re_D is the diametral Reynolds number

*When more than two laboratories are involved in such programs, the test is generally called a "round-robin" testing program. In the program described here where only two laboratories are involved, the term "cross-check" testing program seems appropriate. It is hoped the present program can be expanded to include other laboratories.

The testing program was designed by Mattingly and Spencer of NBS and NEL, respectively, see (3,4). This program continues a number of interlaboratory testing programs that have preceded it, see for example (5).

Reference Systems

The flowmeters selected for purchase by NBS for this testing program are orifice fittings, see Fig. 1. Two such units were sized to measure low pressure waterflow through a 10cm (4 in) diameter pipe at ambient temperature. These fittings were match-fitted to upstream and downstream piping lengths in accordance with orifice practice in the U.S., see (6). The upstream piping length for each of the two meters is equipped with a tube bundle flow straightener see Fig. 2. The piping lengths are aligned with their respective orifice fittings with dowel pins; the flanges joining the upstream piping length and the respective fitting are never unbolted. This assures that variability in the flange joint just upstream of the meter is minimal. The units were nickel plated to minimize the variability of the pipe roughness inside the upstream and downstream piping lengths involved. This minimizes the effects of rusting carbon steel piping. The fittings were also plated for the same reason.

These fittings enable the orifice plates to be removed and re-installed in a highly repeatable, concentric manner in the pipe. The plates are shown in Fig. 3. There are two (2) plates with a nominal beta ratio (orifice hole to pipe diameter) of 0.7 and one plate with a beta ratio of 0.5. These plates are clearly identified by means of scratched markings on their rims which, as shown in Fig. 3, are sealed via neoprene collars. The collars are also marked so that, provided sufficient care is taken, they can be installed in the fittings the same way each time they are used.

A Sprenkle-type flow conditioner has been specially manufactured at NEL for use in this program. It consists of an assembly of three (3) disks, each having 1/16 in. diameter holes drilled in a uniformly spaced configuration with 128 holes per square inch. These plates are mounted by having the largest disk sandwiched in a flange joint and the smaller disks which span the pipe cross-section fastened to the largest by small supporting rods. The axial spacing of adjacent disks is approximately one internal pipe diameter. The entire unit is contained within its own spool piece. This three unit package - 2 meters, each with its own upstream and downstream piping section along with the flow conditioner, constitute the transfer standard. This package was to be tested in a precisely described manner in each of the laboratories.

Testing Program

The testing program is designed to assess each laboratory's processes for determining flow rate and for testing orifice meters. By the careful configuration of the orifice meters and flow conditioner in quite specific ways, the test can be made to generate a very valuable set of data. Using this set of data, one can determine whether the meter runs being tested are influenced by the inlet-flow profile generated in each laboratory facility.

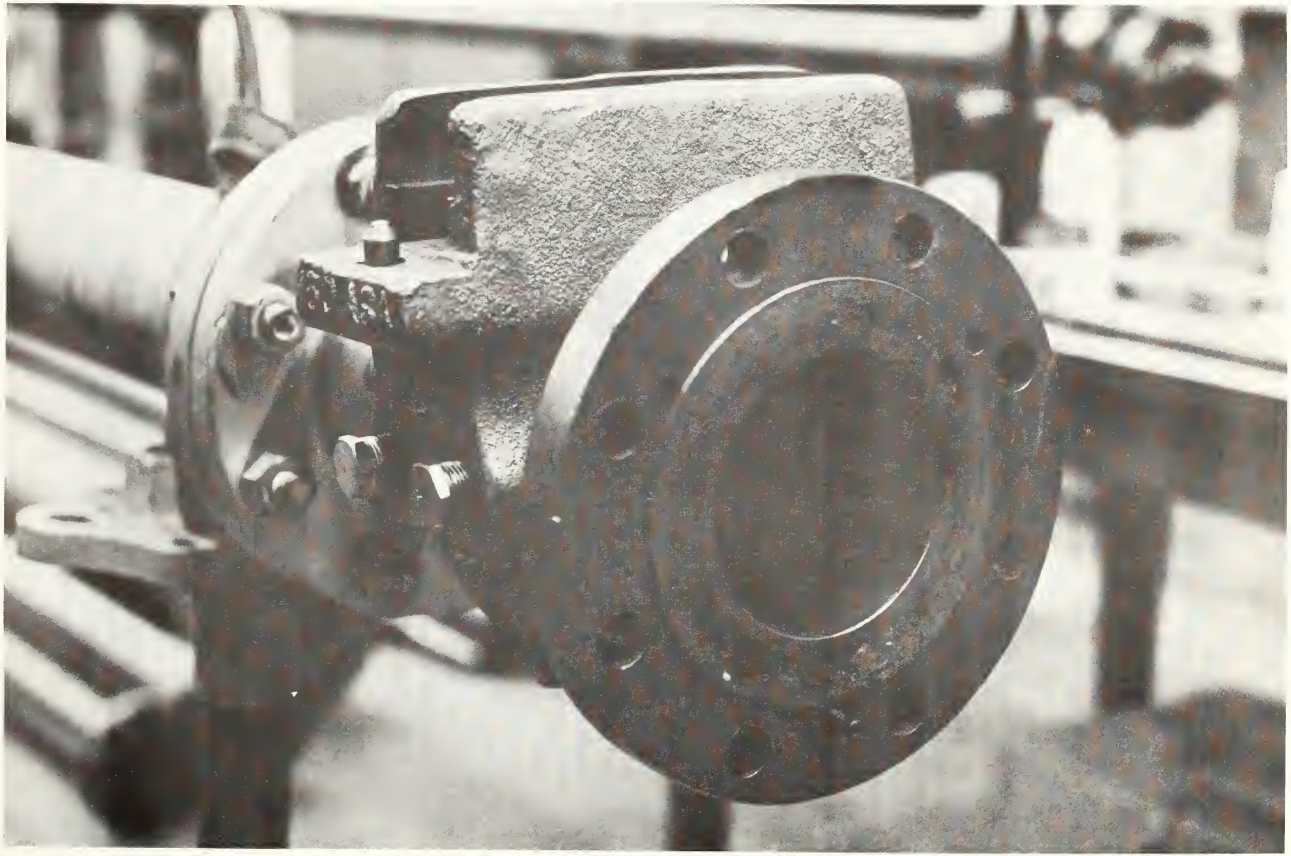


FIGURE 1

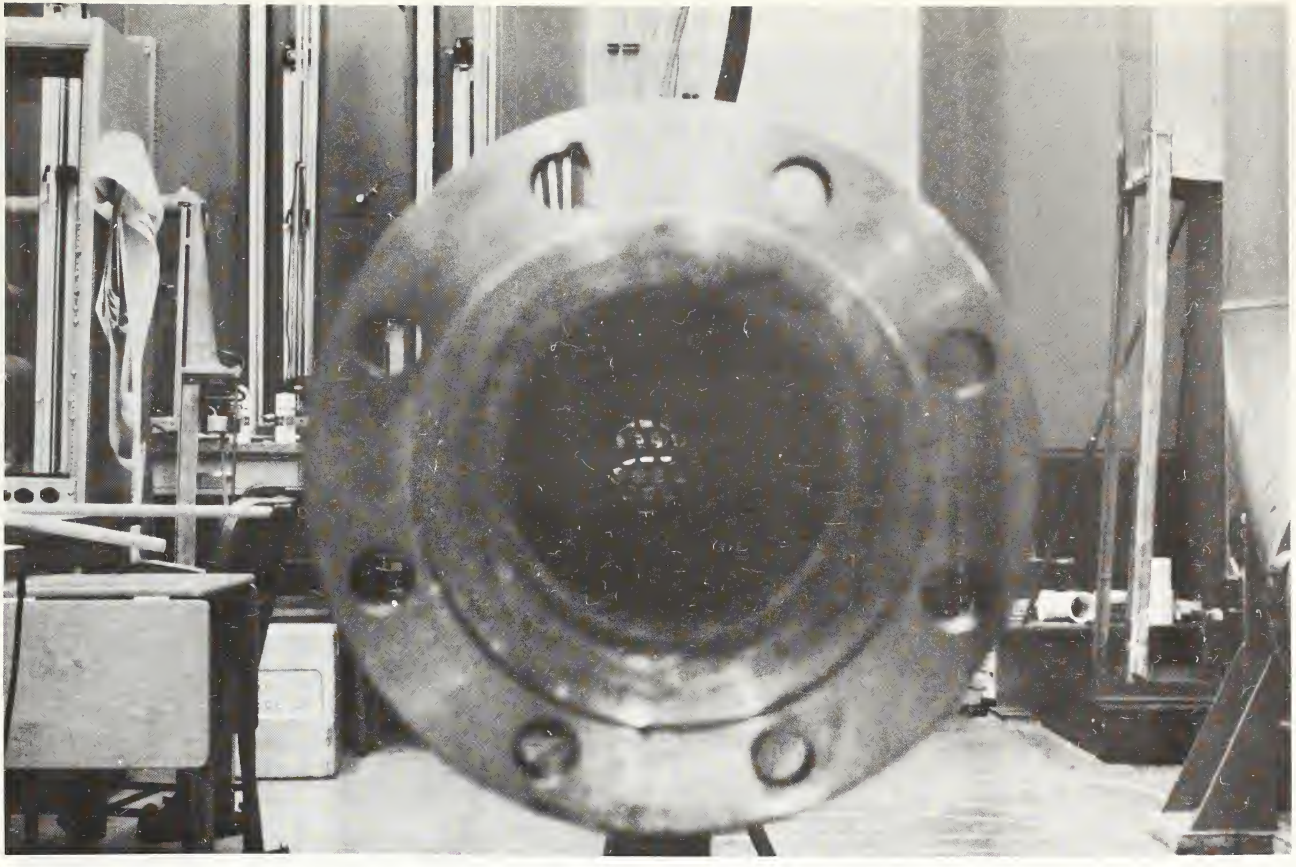


FIGURE 2

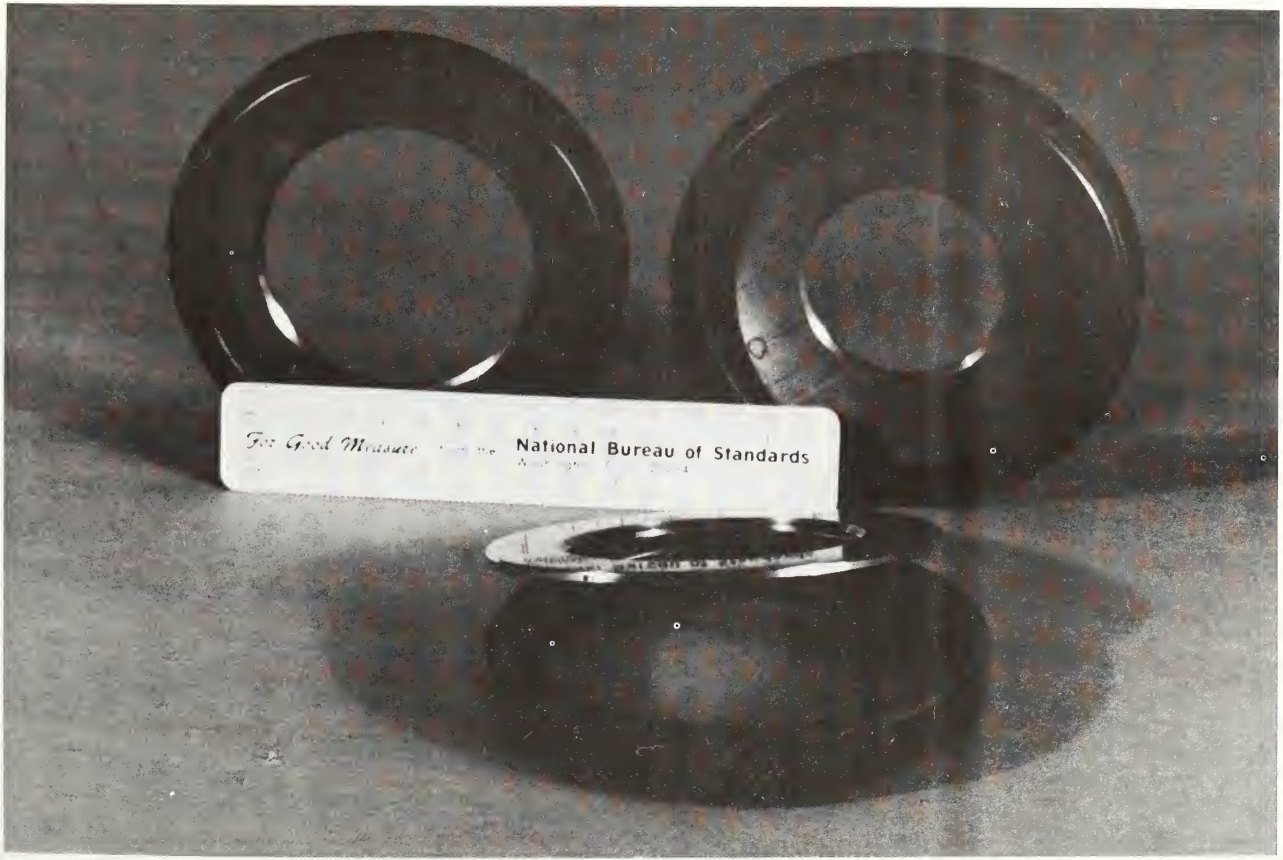


FIGURE 3

The test program is sketched in Fig. 4. There it is shown that both the orifice fittings and the flow conditioner are inserted as one unit into the testing facility. When the meters are calibrated in such a configuration, the results obtained can differ between laboratories because of the different characteristics of the flow entering each meter. The flow from the laboratory piping enters the upstream unit bringing with it the characteristics of the facility piping. The flow entering the downstream meter unit has passed through the upstream meter and the flow conditioner. Because of this, the test results for the downstream meter should not be influenced by the flow characteristics induced by the laboratory piping. On the other hand, the test results for the upstream meter could depend on the flow profile associated with flow through any length of upstream piping including the tube bundle installed in it. As indicated in Fig. 4, the program specifies that the meters are to be tested in each of the two positions. In this way results for each meter are generated both with and without possible effects of the flow profile associated with the upstream laboratory piping. Comparing such results with each other can be very informative and give an indication of the extent of the systematic bias.

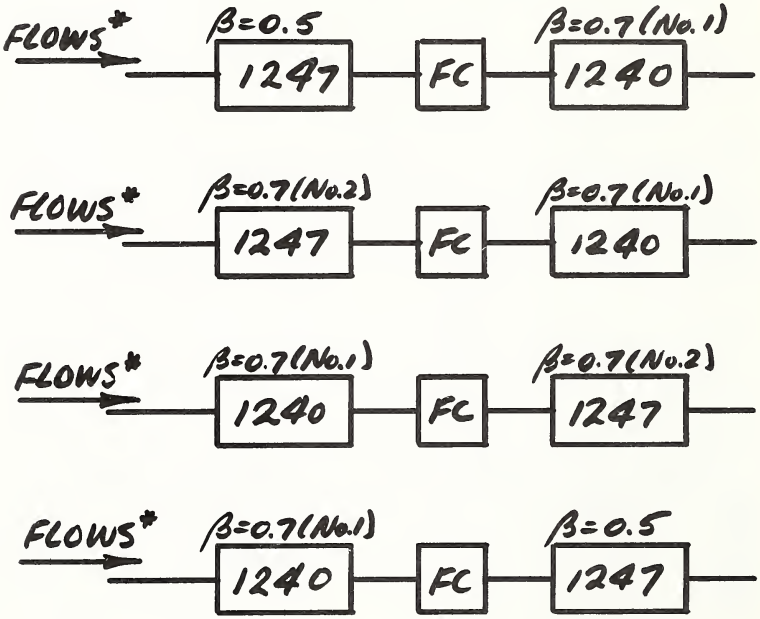
Units installed in tandem are shown in the upper pipeline in Fig. 5. The pressure differential measurement systems used are not shown in Fig. 5. Pressure connections are made using taps placed at the top of the pipe. This allows for testing for the presence of air bubbles in the tubes leading to the pressure transducer. The test is stopped if air bubbles are observed. The bubbles are then removed, and the data associated with that test discarded. Placing the pressure taps at the top of the pipe required that the orifice plates in the meter No. 1247 be installed and removed from the side, see Fig. 5. Fig. 4 also shows that the plate (No. 1) with a beta of 0.7 is not removed from meter No. 1240. In this way, a control is maintained regarding plate positioning.

Results

Typical results for the tests conducted to date are shown in Figs. 6 and 7. Each graph contains a drawing of the metering configuration tested and the designation for the meter which produced the data which is plotted.

Fig. 6 indicates the interlaboratory comparison for the beta = 0.5 orifice plate in the upstream position. The agreement between the open symbols shows that the mean values for the discharge coefficient obtained at the two laboratories compare very closely. The error bars on the symbols indicate two standard deviations computed for the multiple weighings done at each flowrate. As indicated in Fig. 4, a pair of tests is carried out at each flow rate. The pumps are switched off during the time period between the two tests. The degree to which the open symbols of the same shape are close vertically is a measure of the labs "switch off - switch on" repeatability. The degree to which the open and closed symbols of the same shape compare is a measure of the repeatability of the measurement at the same laboratory from year to year. The agreement between NBS and NEL is shown to be about $\pm$ 0.1% for the mean values plotted. The largest deviation occurs at the highest flowrate tested.

NBS-NEL ORIFICE CROSSCHECK



* FLOWS:

1. $Re_D = 1.5 \times 10^5$
2. $Re_D = 2.1 \times 10^5$
3. $Re_D = 3.5 \times 10^5$

SWITCH-OFF

REPEAT

FIGURE 4

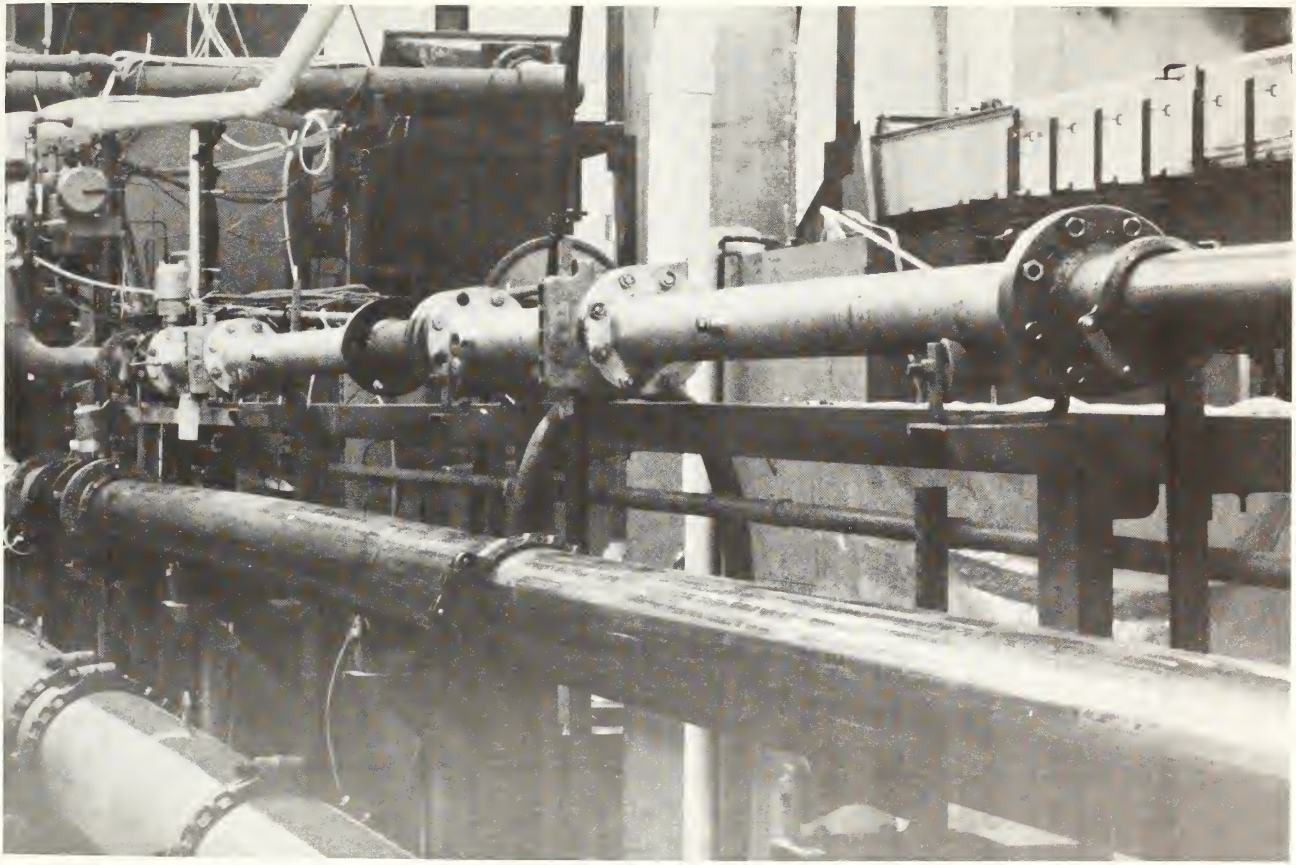


FIGURE 5

Fig. 7 shows the data for the downstream meter containing the beta = 0.7 plate which is not removed from meter No. 1240. In spite of the fact that this meter receives "conditioned" flow, variations are noted to be larger than those observed in Fig. 5. Comparison of the open symbols indicates the data for the mean values at all flows tested is within $\pm$ 0.15%. The data given by the closed circles seems to indicate an upward shift in the mean values of approximately 0.3%. Such a shift could be due to a change in the meter which, although not apparent in visual inspections of the plate and pipe lengths, is present and affects the results shown. Whether or not this interpretation is correct should become apparent when subsequent testing is carried out in the other laboratory, i.e., NBS. If this upward shift is also found in the NBS results, it will be concluded that the two laboratories remain close in their flow measurement processes. However, if the upward shift is not repeated in subsequent testing the source of the variation will need to be determined.

Several aspects of interlaboratory testing are illustrated in Fig. 7. Most obvious is the fact that when more laboratories are involved in the test, the best estimate of the "true result" can be made more credible. When only a small number of laboratories are involved, it is possible for one or another (or none) to be close to the "true value". That test results repeat precisely in the same lab from test-to-test does not necessarily imply that the repeated value is correct. In fact, a sudden shift at anytime of the results from a particular laboratory can be a shift to the correct value. When a large number of laboratories participate in this type of program and when these labs perform their measurement processes using different techniques, increased confidence can (and should) be placed in the central value over the range of the results. For this reason, tests such as this orifice cross-check can greatly benefit from being extended to other laboratories interested in participating.

Finally, it is concluded that these tests should be conducted on a continuing basis between or among the participating laboratories. Only in this way can the fluid flow measurements be properly assured to be as good as they are claimed to be. When this is so, the custody transfer of all the valuable fluid products via fluid meters can be done with the satisfaction of buyer and seller alike.

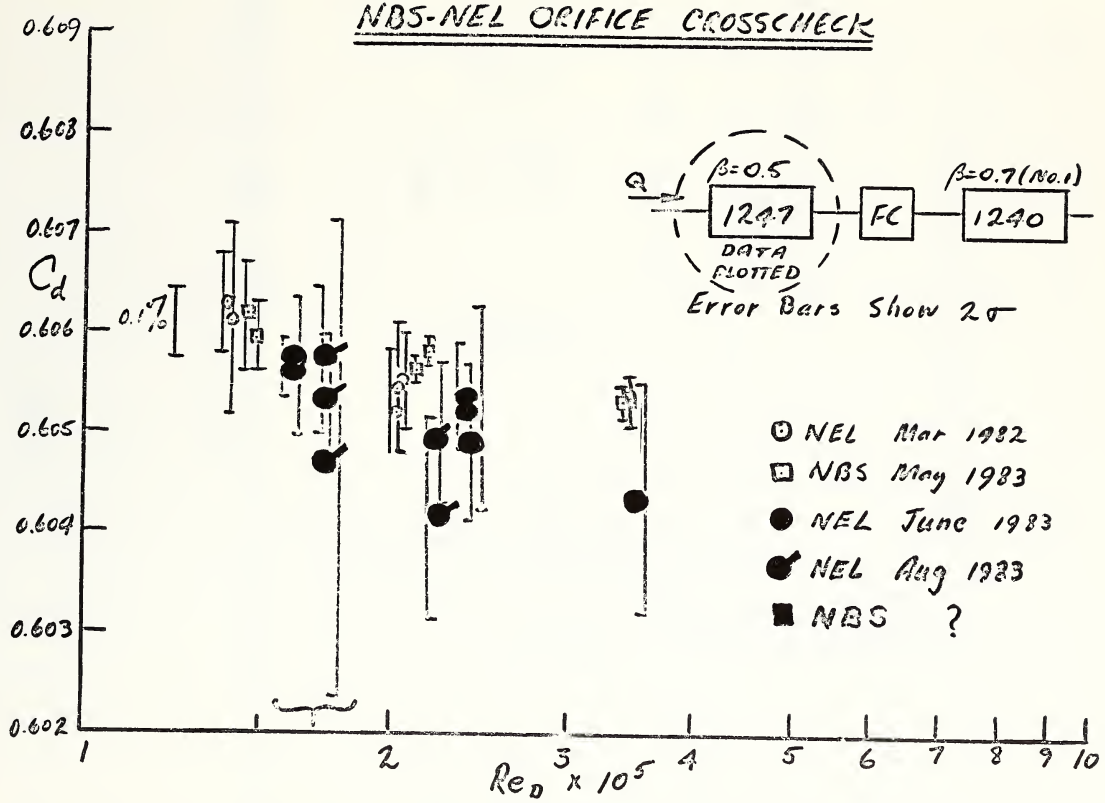

NBS-NEL ORIFICE CROSSCHECK
0.609
0.608
0.607
C_d
0.606
0.605
0.604
0.603
0.602
0.1%
β=0.5
1247
FC
β=0.7(No.1)
1240
DATA PLOTTED
Error Bars Show 2σ
NEL Mar 1982
NBS May 1983
NEL June 1983
NEL Aug 1983
NBS ?
1
2
3
4
5
6
7
8
9
10
$Re_D \times 10^5$

FIGURE 6

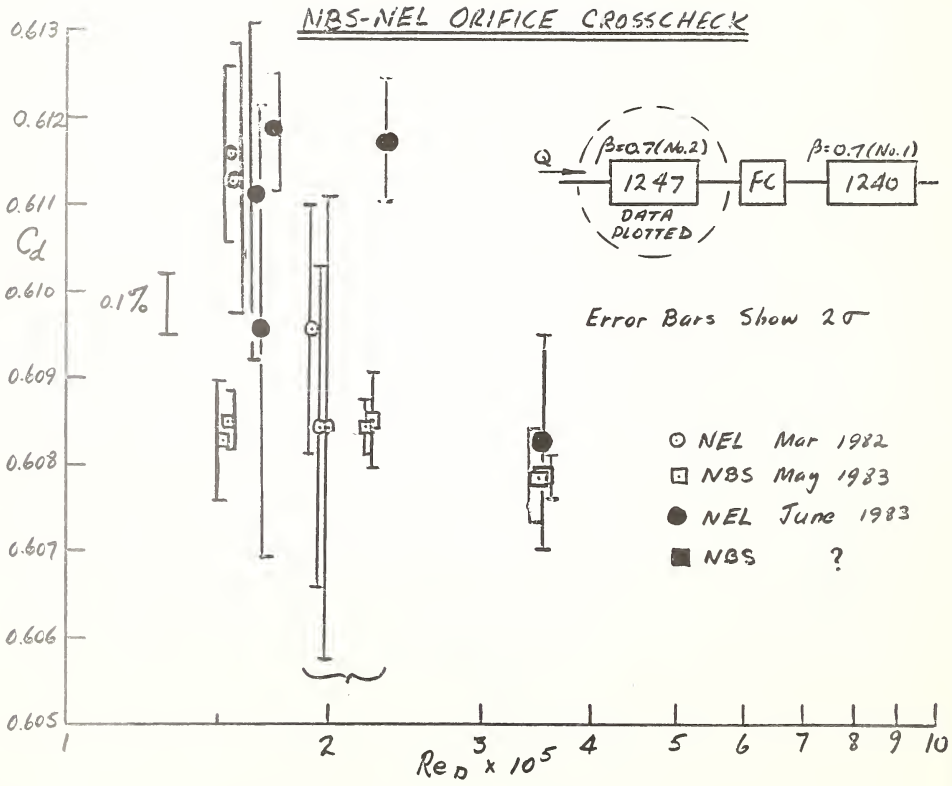

NBS-NEL ORIFICE CROSSCHECK
0.613
0.612
0.611
C_d
0.610
0.609
0.608
0.607
0.606
0.605
0.1%
Q
β=0.7(No.2)
1247
FC
β=0.7(No.1)
1240
DATA PLOTTED
Error Bars Show 2σ
NEL Mar 1982
NBS May 1983
NEL June 1983
NBS ?
1
2
3
4
5
6
7
8
9
10
$Re_D \times 10^5$

FIGURE 7

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Orifice Meter Testing in Water at NBS-Gaithersburg

J. R. Whetstone
National Bureau of Standards
Gaithersburg, MD

Introduction

An orifice meter testing program has been initiated by the American Petroleum Institute (API) at the National Bureau of Standards (NBS) laboratories in Gaithersburg, MD. This program is designed to characterize the performance of orifice meters in an intermediate Reynolds number range (1,000 - 2,000,000). The approach is to produce discharge coefficient data in water flows over a range of pipe sizes for number of different beta ratios (orifice hole to pipe diameter)orifice plates. The basis for the testing will be the NBS water flow calibration facility. An API steering committee has been appointed to monitor progress and review results.

Orifice Meters

The orifice meters planned for testing consist of two sets of meter runs in five (5) nominal line sizes (5.1 to 254 cm diameter) with two (2) sets of orifice plates (0.1 to 0.75 beta ratio) one for each meter run. Thus, 140 combinations of plates and pipes can be tested. The meter runs are flange tapped. The plates were fabricated to natural gas (U.S.) standards and are the joint property of the American Gas Association (AGA) and API. This set of meters and plates includes the set being tested at the NBS laboratories in Boulder, Colorado as described earlier in this report by Mr. Brennan.

The Test Program

The test program will be conducted over a water flow range

$$10^3 \leq Re_D \leq 2 \times 10^6$$

where Re_D is the diametral Reynolds number. The Reynolds number range for the planned water flow test will overlap the Reynolds number range of the Boulder tests. Water pressures will be less than 400KPa (58 psi); temperatures will be at or near ambient, i.e., less than 40°C.

Differential pressure across the orifice meters will be measured using oil filled pressure transducers. Two different differential pressure transducers will be used - one based on piezoelectric principles, the other on a quartz bourdon tube. Levels of oil in the transducers and the connecting tubing are monitored at the oil-water interface and are visually adjusted to equal heights using a telemicroscope. The differential pressure transducers are calibrated using two dead weight testers. The transucers have been tested on orifice meters by connecting both transducers to one pair of flange taps. The meters used were the NBS orifices that are part of the NBS-NEL orifice crosscheck program described earlier in this report by Mattingly. The agreement between the two units in these tests is shown below for five consecutive runs.

Run No.	Transducer Pressures #1 mean	#1 s.d.	#2 mean	#2 s.d.	No. of Observations	Divert Time
16	3.0362	.0422	3.0336	.0217	52	50.665
17	2.9629	.0338	2.9627	.0115	52	50.721
18	3.0090	.0349	3.0133	.0174	51	49.919
19	2.9971	.0382	2.9989	.0135	51	49.863
20	3.0304	.0443	3.0233	.0171	51	49.833

The orifice meters will be piped into the NBS water flow calibration facility so that the flange taps are in a vertical plane. The water flow into these runs will be flow conditioned using Sprenkle-type flow conditioners. These will be installed in upstream spool pieces having diameters 5 cm larger than the meter run tested. An appropriately sized reducer will connect the spool piece to the upstream section of the meter run tested.

Dimensional measurements made to date include the lengths and diameters of the meter runs and the diameters and thicknesses of the orifice plates. The inside diameters of the meter tubes were measured using an intermicrometer which determines circular diameters from three contact points on the circumference. This unit is calibrated using a proving ring. The intermicrometer is sized to permit the measurement of pipe diameters at various stations up to approximately one to two pipe diameters from the flanged ends of the different pipe sections.

Reference Flow System

The flow reference system is shown schematically in Fig. 1. A complete description is given in (1). This system uses gravimetric techniques to measure the amount of water diverted into the collection tanks during a flowrate measurement. The timed collection of water is controlled by the computer of the data acquisition system. Handwritten data is purposely kept to a minimum to reduce transcription errors. Water temperatures, differential pressures across the orifice meters and collection times are transmitted via data buses to the computer. The data are processed, square roots of the differential pressures are taken and the results averaged. Results, data and calculated discharge coefficients are filed on computer disks for transmission to the steering committee and to API in appropriate formats.

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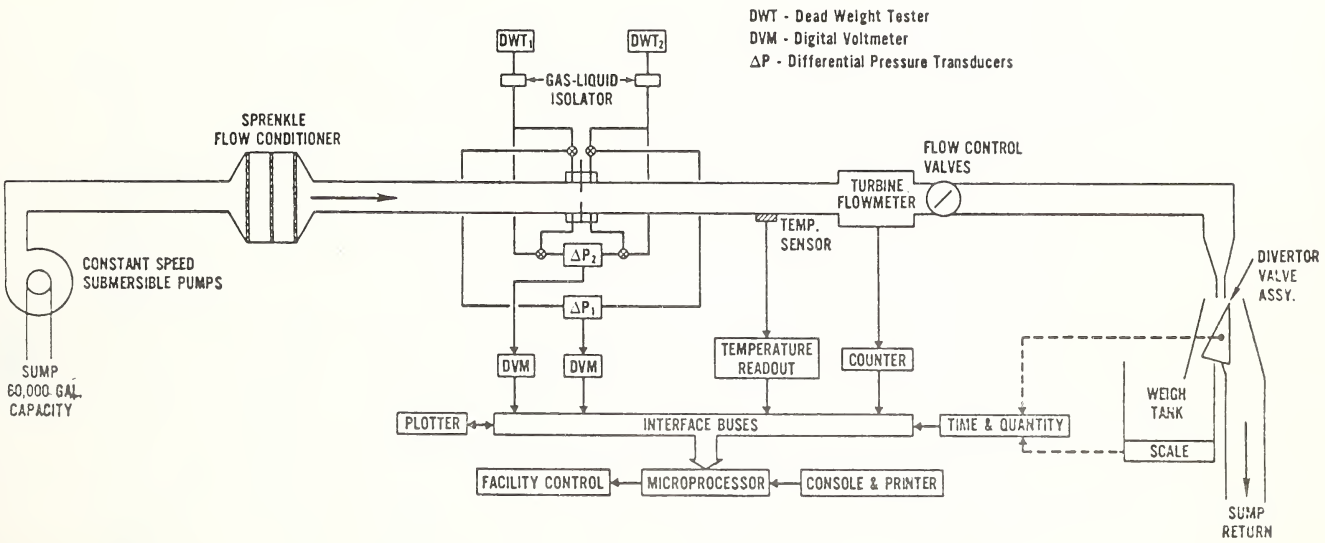

DWT - Dead Weight Tester
DVM - Digital Voltmeter
ΔP - Differential Pressure Transducers
DWT1
DWT2
GAS-LIQUID ISOLATOR
SPRENKLE FLOW CONDITIONER
FLOW CONTROL VALVES
TURBINE FLOWMETER
TEMP. SENSOR
ΔP2
ΔP1
CONSTANT SPEED SUBMERSIBLE PUMPS
DIVERTOR VALVE ASSY.
SUMP 60,000 GAL. CAPACITY
DVM
DVM
TEMPERATURE READOUT
COUNTER
WEIGH TANK
PLOTTER
INTERFACE BUSES
TIME & QUANTITY
SCALE
FACILITY CONTROL
MICROPROCESSOR
CONSOLE & PRINTER
SUMP RETURN

FIGURE 1

INTRODUCTION TO THE TASK GROUPS

M. Klein
Gas Research Institute
Chicago, IL

The designers of this workshop had two kinds of objectives in mind. First, they wanted to produce a consensus as to the identity, character and seriousness of the specific limitations in the current orifice metering state-of-the-art and, simultaneously, to determine whether these limitations might be amenable to removal by the application of research capabilities currently available in the field of fundamental research in fluid flow. The stage for attaining these objectives has been set by the presentations of this morning. The current situation in metering was described by Miller; basic flow phenomena and the current research capabilities in fundamental fluid flow research described by Mattingly and by Ghia.

Accomplishing the workshop's goals requires bringing together the representatives of both the metering and research communities in close interaction. That interaction needs a forum for active discussion. To produce such a forum, we have organized four task groups and have made an attempt to populate each of them with representatives of both these communities. We hope in this way to develop discussions in each group around the points of view of both communities. It is hoped that a common perspective might be developed in the ensuing discussion. The first two of the four task groups deal with subjects which are clearly of simultaneous interest to fundamental research and to flow metering engineering. The third task group has an extra emphasis on practical metering techniques and the fourth a substantial emphasis on practical calibration and standards related problems.

The mechanisms of how these objectives might be accomplished were considered very carefully by the organizers since it was felt by them that the productivity of the workshop could be strongly influenced by its structure. Many different formats were examined and discarded and eventually a plan was produced. The plan was based, partially, on the belief that the optimum size for a discussion group composed of experts from diverse technical fields and disciplines in which intensive discussion could be produced and maintained was perhaps around 20 people. Since it was expected that the workshop might attract 80 attendees, it seemed appropriate to split the workshop into four different smaller working groups.

It was decided that each group should deal with the central subject of the overall workshop - namely, the identification of research projects for improving metering by orifice plate meter runs - but from quite separate viewpoints.

The four were identified as:

a) the study of the effect on metering results of the pattern of the flow and the geometry of the orifice plate and the adjacent pipe near the orifice plate;

b) the study of the effect on metering results of the pattern of the flow inside the meter itself as influenced by the pipeline and fitting configuration well upstream of the orifice plate;

c) the practical aspects of orifice measurement - the determination of the characteristics of the flowing fluid, i.e. density, viscosity, etc., and the measurements which are needed to establish rate of flow, i.e. differential pressure, gas density, etc.

d) determination of procedures for evaluating the accuracies of laboratory calibrations and facilities, of written specifications and standards, etc., with emphasis on those already published.

The Four Task Groups were thus created and within each Task Group a mixture of experts were selected from the list of expected attendees by the organizers. The choice of leaders for the groups was governed by the selection of the subject content which it was hoped the groups would attach.

The Chairmen and Vice-chairmen were advised of the planned objectives well in advance and were invited to join the organizers the evening prior to the start of the workshop to discuss workshop goals. This latter proved immensely valuable with many good ideas produced which were absorbed into the operation of the workshop.

The above-mentioned overviews preceded the meeting of the task groups and were designed to place the historical and practical aspects of orifice metering practice and problems into perspective. Additionally, we wanted to exhibit the fundamental research capabilities for modeling flow phenomena, and establish a consensus as to the resources needed which might be used in research programs aimed at solving the fluid dynamic behavior in orifice metering systems.

As already stated, the first of the four task groups is concerned with problems associated with upstream effects. It is hoped that discussions in that group will be concerned with the kind of basic and engineering research necessary to reduce the variability in meter performance which results from variability in the upstream conditioning of the flow field.

The second task group deals with problems associated with the behavior of the flowing fluid within the meter itself, i.e. in the vicinity of the orifice plate, and the effect of this behavior on the accuracy of metering. The discussion in that group should cover the potential role of fundamental research in understanding the flow inside orifice meters and should attempt to identify the limitations on the accuracy of metering which appear to result from this fluid behavior. This group will probably propose research projects which are mainly fundamental in nature, but can also propose projects which contain testing components. These could be aimed at removing some of the perceived suspicions of conclusions reached via "basic research" and should furthermore be aimed at reducing the variability in meter performance described in the overview papers (especially that of Miller).

The third task group is asked to consider the practical problems which the engineering community meets in the field. Research proposed by this group will probably be mostly of the testing kind but their list should also contain those projects which have a potential for producing any fundamental understanding which might be required to solve these problems. This task group should try to produce a consensus as to the current state-of-the-art in orifice performance and as to the potential for moving that state-of-the-art forward to produce higher levels of accuracy.

The fourth task group is asked to discuss the possibility for developing a dynamic international calibration system which might replace the paper standards currently in use. It should also consider the possibility for designing substantial laboratory intercomparisons and should look at the problem of establishing documented field accuracies.

The task groups will first meet, list and discuss issues and arrive at preliminary conclusions. The task group leaders will then present preliminary reports of these discussions to the entire workshop. These preliminary reports should be aimed at producing a "cross fertilization" among task groups in their second meetings. After the second set of discussions, the task group leaders will meet again, producing a list of recommendations considered "important for improving orifice performance".

The recommendations of the task groups will be restated by the workshop organizers in a form appropriate for inclusion in a ballot which will be distributed to the attendees. Each attendee will be asked to assign priorities to the various recommendations on the ballot form. The workshop organizers will analyze the results for inclusion in the workshop report. The results of the ballotting will be quite useful and informative since the ballot will give the attendees the opportunity, individually, to synthesize the total set of recommendations within the framework of their own sets of experiences.

TASK GROUP I

UPSTREAM FLUID FLOW CHARACTERISTICS AND THEIR EFFECTS ON OFIFICE METERING

Chairman, F. C. Kinghorn
National Engineering Laboratory
East Kilbride, UK

Vice Chairman, R. W. Miller
The Foxboro Co.
Foxboro, MA

The Chairman presented the following report of the Group's work.

Problems to be Tackled

Task Group I began its deliberations by trying to define the problems in its mandated area along the lines laid down by the workshop organizers.

The first problem discussed by the Group was very easy to define, although it is not very technical. Despite this, it is perhaps the biggest problem of all and might well be the hardest one to solve. It is that the metering community must be persuaded that accuracy costs money and that solutions to the problems raised here will cost non-trivial amounts of time, money and manpower. In other words, that it is never possible to get something for nothing or, put another way, you get what you pay for.

Having said that, consider now the more technical problems discussed in the Task Group. The first is that it is necessary to understand how changes in flow conditions affect the response of an orifice meter before being able to provide corrections for upstream flow effects. By flow conditions are meant not only the velocity profiles entering the meter but also other details of the flow such as turbulence levels, pulsations, etc. Thus, upstream effects are not completely specified by a description of which pipe fittings exist upstream of the meter, as is normally considered to be the case by the engineer in the field. (This identification with fittings, of course, stems from the fact that only the modification of fittings, valves, etc. is at the disposal of the engineer in the field and so he tends to see these physical components as the sole cause of disturbances). In other words, a description of the flow field is not taken simply as a statement of the time-averaged profiles themselves. This distinction is essential because considerable work has already been reported in which the effects of various upstream fittings, (e.g. single bends, double bends, etc.) have been examined empirically at various distances upstream of orifice plates. It is essential that this empirical work be understood in some detail, as a function of any changes which take place in flow situations. It is essential to be able to relate changes in upstream flow conditions to detailed changes in the flow as it goes through the orifice plate. Without this, it can never be possible to relate the observed orifice plate response to combinations of changes in upstream conditions.

The next problem area which the group identified dealt with the need to be able to develop methods for creating similar flow conditions at the orifice plate regardless of actual upstream conditions. By this is meant attempting to develop a hardware package consisting of a flow straightener and an orifice plate. The operational goal set by the Task Group was that the coefficient of the orifice plate in the package would not change by more than perhaps 0.1% for all possible upstream flow conditions which realistically can be expected to be met in practice. Ideally, the flow conditions produced at the orifice plate would be similar to those carefully controlled flow conditions under which all of the existing reference data for orifice plates were obtained. The Group did not ignore the possibility that this might not be possible to achieve in practice. If it is indeed found to be impossible, it might be necessary to attempt to create some other convenient, known and repeatable flow condition at the orifice plate regardless of the actual upstream disturbances present. This, in turn, might require the starting of a large new program for determining the coefficients of orifice plates downstream of whatever straightener is developed for inclusion in the package. In such a program, plates and runs of different diameter ratios would need to be tested in order to determine the discharge coefficients for the arbitrary "standard" flow field that is produced by this straightener.

The final problem area considered by the Group dealt with the need to quantify the effect on orifice plate response of having upstream straight lengths of pipe which are shorter than specified by the standards. This is especially important in installations where flow straighteners are not used. This problem area is of considerable practical interest currently for very many of the orifice metering installations in existence. It is generally very difficult or, at least, impractical to change the geometries of those existing installations which do not presently conform to the standards. It is therefore absolutely essential for the operators of such installations to know the effect of such deviations from the standards on the accuracy of their measurements in order for them to be able to estimate their operating accuracies. It should be emphasized that the accuracy desired by these operators is not always 0.1%; indeed it may not even be 0.5%. Sometimes 3% accuracy is quite adequate in some applications.

The current ISO standard states that a straight length of 40 pipe diameters is necessary for certain pipework configurations in order to obtain the accuracy promised in the standard. Suppose, however, that an installation happens only to have a straight length of 25 diameters. Now, in cases for which there are deviations from the ISO standard, that standard adds an additional 0.5% uncertainty. This is based, however, on the assumption that only slightly reduced lengths will be found in practice, and thus takes care of only one narrow aspect of the problem and then only does so on the average. It was felt that it is far more important for the standard to be able to state more generally how to relate a reduction in straight length from the standard length to a corresponding change in the uncertainty in the orifice plate measurements.

Task Group I thus identified four problems, the first of which is philosophical and which everyone working with the subject of orifice metering will need to attack. The remaining three are the technical problems which the Group felt are of most importance in connection with the effect of upstream flow conditions on orifice meter response.

Research Projects Required

Next the Group discussed the question of designing and developing actual research projects and how these might be put together to bring about solutions to the practical problems just defined. Broadly speaking, there would be two approaches to tackling these research topics, although it was recognized that to be most effective these should be complimentary. The two approaches are the computer modeling of flow approaching and through the orifice plate and fundamental experimental measurements on flow systems.

It was the opinion of the Task Group that computer modeling could be used in three ways.

(i) For trying to predict the dependence of the orifice plate response on changes in flow conditions. In other words, the effect of deviations from ideal flow conditions is of interest. This concentration of emphasis might simplify the computational structure, and the objective might be easier to achieve than that of completely defining the entire flow field in absolute terms.

(ii) To determine which diameter ratios and tap locations are least sensitive to particular changes in flow conditions. This would then give some guidance not only on which orifice meters might be expected to give best measurement results but also for what conditions these best results might be obtained. It is known, for example, that the response of an orifice meter to any given flow disturbance is not uniform over the whole range of diameter ratios, and is not always even in the same direction. Computer modeling could thus give guidance not only on which orifice meters might be expected to give best measurement results but also for what conditions these best results might be obtained and which beta values should be used in particular practical situations.

(iii) To assist in the development of a flow straightener/orifice plate package by allowing for rapid modification and evaluation of various designs without having to carry out empirical tests in every case; although the overall program of straightener development would be largely experimental.

The concept of developing a package consisting of a straightener and an associated orifice plate which is insensitive to upstream flow conditions does not necessarily mean that the straightener which would be developed would produce a fully developed profile, although that would be best. It may simply be, as already mentioned, that the profile produced by the

straightener would be independent of the upstream flow conditions. It is very important that any such straightener developed have the minimum possible head loss and is not susceptible to being blocked by solid matter in the flow.

Estimating the effect on metering accuracies of using straight upstream lengths that are shorter than those required by current standards can start with an extensive literature survey since much information has already been published on this. It was felt that it would be extremely useful to try to develop a catalog of correction factors which would be produced after completing an experimental program designed to fill in existing gaps in the data. There would be no way to avoid mounting an extensive test program but the work could be minimized by first identifying the pipework configurations which are most commonly used. The measurement and testing efforts would need to be closely coupled to the computer modeling work. This could be a very time consuming research project but its results would be very valuable. If the research were done in a coherent manner by coordinating work in different laboratories around the world, the amount of time required might be minimized and the results put together quite efficiently. It was felt that the catalogue should be in the form of a table which would list types of disturbances, ranges of beta ratios and types of pressure taps, giving for each of these the correction factors by which to multiply the indicated flow to yield a better estimate of the actual flow. Obviously, this would imply an increased overall uncertainty in the discharge coefficient which is used, and there would be different tables for different uncertainty levels. It would, on the other hand, at least be a step towards knowing what the actual uncertainty might be under various combinations of conditions.

Resources Required

To some extent it was necessary to pick estimates for the numbers associated with these resources almost out of thin air. Consider first the computer modeling effort. It was said by the experts at this workshop that, in the initial stages of the modeling developments, it would be necessary to work towards describing axially symmetric, laminar, incompressible flow. There was a feeling that perhaps two man years would be needed to develop the basic program needed to describe such a limited case and another man year to run a number of particular situations for it. Of course, once the basic program became available, it would become possible to run many situations without much additional effort.

There is great uncertainty as to the resources which would be required for studying the general situation of asymmetric, swirling, turbulent and compressible flow. The Group felt that something like twenty man years might be needed for that. The computing power used was not discussed specifically so that these numbers should be taken as referring to present computing power but the difficulty in predicting the rate at which progress could be made on the purely technical aspects is so great that modifications to estimates on the basis of improvements in computing power are unlikely to be critical.

For the design of straighteners, which is really a parallel project, similar levels of resources are required. It was estimated, in this case, that about three man years would be needed in order to arrive at something which deals with a simple laminar, symmetric and incompressible flow. Here again much more in the way of resources, perhaps twenty man years, would be needed to be able to do something in any depth on flow straighteners for the general case. The experimental development of the straightener could proceed in parallel with some of the computer work. The Group did not actually come to any conclusions as to how long it would take to complete the evaluation of any package which might be developed. Rather arbitrarily, the chairman said that he estimated this at about four man years to run through a fair number of situations with a flow straightener package.

Resources other than manpower are also needed and it is obvious that appropriate facilities are essential. These are available at a number of installations world-wide.

The resources required for doing research on the final topic, that of developing a catalog of correction factors to compensate for upstream lengths which are shorter than are currently required were hard to estimate. Ten man years seemed probable to produce a table which, while not comprehensive, would be sufficiently broad in coverage to be used by a variety of people.

Implementation of Research Project Results

The main point established in this part of the discussion was that the potential users of the results of these recommendations must have confidence in the resulting information and recommendations. Thus, whoever provides the information must have high credibility as an independent and impartial organization. Furthermore, experience in the field must be built up as quickly as possible. Thus, as soon as any results begin to be obtained, the users must be convinced to try them. The information on the research results obtained must therefore be disseminated rapidly. Such vehicles as NBS reports are obviously an excellent way for doing this as are the normal publications media.

It was also believed that it would be useful if, in perhaps three years time after the start of the proposed effort, it were possible to have a workshop where, instead of talking about existing problems as in this instance, it would be possible to describe what had been done about the problems previously discussed and how particular problems then current in the field could now be solved. This requires that there be confidence in those who will have provided the new information and that there already would be some experience in the field in using it.

One other topic covered dealt with was an assessment of benefits to be realized from any successful results. There are some fairly obvious benefits. If the straight length of pipe upstream of the orifice plate can be reduced, there would follow a direct reduction in the cost of piping and, more importantly, in savings in space. If accuracy is increased, international

trade will benefit from the increased confidence in the measurements. Increased accuracy would result in fewer arguments among the nations as to the relative merits of different methods of measurement. Finally, as regards accuracy itself, it was felt that this would be quite cost effective in process plants where a producer might be producing a product but perhaps might be operating inefficiently because of inaccuracies in the metering of the quantities of flow of the constituent material. Improving the accuracy of metering could reduce costs considerably for such a person. In fiscal situations such as custody transfer, the presence of inaccuracy results in one person winning and another losing. There is, therefore, the possibility of minimum net cost benefit overall. Since it is possible for one side always to lose and the other always to win, however, there is the distinct possibility for inaccuracy to produce an unfairness in trade. Improved accuracy can therefore be expected to improve equity in the marketplace. An increased efficiency in developing contracts would therefore result from improved accuracy.

TASK GROUP I PROJECTS

The Task Group's proposals can be summed up in the following headings for key projects:

1. Through a literature survey, gather information on the nature of flow conditions generated by pipe fittings and pipework configurations, and on how these can be improved.

2. Survey industrial practice to identify the most commonly occurring configurations of pipework and fittings which generate disturbed flow.

3. Use a combination of computer modelling and experimental testing to predict
   - the effects of changes in flow conditions on orifice plate response
   - the diameter ratios and positions of taps which are least sensitive to changes in flow conditions
   - the design of a straightener which will transform a wide range of flow conditions into one standard form with the minimum possible head loss.

4. Develop a straightener/orifice plate package which is insensitive to changes in upstream flow conditions.

5. Produce a catalogue of correction factors to compensate for the effects of the most commonly occurring fittings installed at various distances upstream of the orifice.

TASK GROUP II

FLUID PHENEMONA IN ORIFICE METER GEOMETRIES

Chairman, Prof. R. A. Bajura
Mechanical & Aerospace Engineering
West Virginia University
Morgantown, WV

Vice Chairman, Dr. R. C. Mottram
Dept. of Mechanical Engineering
University of Surrey
Guildford, UK

Task Group II concerned itself with four topics

1. Experimental and Numerical Studies of Steady, Incompressible Flow
2. Pulsatile Flows and the Dynamics of Secondary Systems
3. Wet Steam and Gas Flows
4. Compressible Flows

This summary description is supplemented by Appendix 1, which contains a more detailed description and prioritization of topics addressed during Task Group II's deliberations. There appears to be good agreement within the fluid dynamics community regarding topics to study and experimental methods of attacking the flow in orifice geometries.

Topic 1. Experimental and Numerical Studies of Steady, Incompressible Flow

Topic 1 addresses the basic problem of understanding incompressible flow through orifice meters and focuses on the flow field itself without the additional complications of pressure measurement and the mechanical aspects of flow metering. Many subtopics were identified during the discussions. In order to establish a workable terminology, the research problems and experimental methodology identified during these discussions will be labeled as Subtopics. An expanded description of these areas of interest follows.

A. Subtopic 1 - Flow Visualization

This subtopic refers to studies of the fundamental details of the orifice flow field. Considerable interest was expressed in continuing flow visualization work. The approaches mentioned include the use of hydrogen bubbles, dyes and birefringent fluids for liquid flows, and the use of oil smoke for air flows. The objective of the visualization work would be to identify streamlines, shear zones, recirculation patterns, and eddy zones. A strong recommendation was made that these flow visualization studies be done in such a way as to correlate with the signals obtained from devices associated with normal meter operations such as the measurement of static pressure, differential pressure and velocities at different points in the field.

B. Subtopic 2 - Basic Flow Measurements

Research on basic flow measurements requires looking at the entire flow field. Many flow measurements were suggested as being of interest. These included measuring mean and turbulent velocity profiles at different points, the study of reattachment points (not only to specify their time-averaged locations but also the study of their time-varying motions) and the wall pressure distributions along the pipes (including instantaneous and average values).

The velocity and wall pressure profiles would provide an indication of the shape and size of eddy motions in the orifice flow field. Multiple point velocity and pressure measurements were suggested to correlate the velocity at one point with the pressure measured at another point. This effort should not be restricted to the flow just upstream and/or just downstream from the orifice plate, but must also include detailed studies across the flow field to produce a complete understanding of the flow through the meter. Thus, the required investigation would, in effect, look at both the upstream and the downstream portions of the flow field simultaneously.

This work should include studies of any coherent fluid flow structures present, including, among other things, the identification of instabilities in the orifice jet and the sensitivity of this jet flow to different impulses present upstream. It is necessary in such work to measure both fluid velocity and pressure fluctuations, their power spectra, and the probability density functions. This data gathering task might lead to the production of more results than are needed for meter and installation design but it would provide a more complete picture of the orifice flow field. The objective of these studies is to characterize any unsteadiness in the otherwise steady flow. Ultimately, it will be necessary to perform experimental tests in controlled laboratory studies, computer modeling simulations, and even calibrations, to determine the specific effects of each of these characteristics on the discharge coefficient.

Task Group II felt that flow perturbation studies should be started as soon as the salient flow phenomena are identified. These studies would examine the effects of different perturbing conditions on the discharge coefficient. Perturbing effects might include changes in the upstream velocity profiles, changes in the thickness of the plate, changes in plate and pipe roughness, and other factors.

Subtopic 3. Calibrations and Field Measurements

Since conventional calibrations were considered to be the province of Task Group III, very little of our discussion concerned calibration. Suggestions that were made in the area of calibration included tests needed to extend the Reynolds number range of the data, work aimed at studying the effects of compressibility, comparisons of laboratory results with field measurements, and using microprocessors and other electronic equipment to accomplish on-line

computing of the discharge coefficient. On-line computing will incorporate instantaneous values of pressure and any other useful rapidly varying characteristics into the flow computation.

Subtopic 4. Flow Models

Flow modeling is meant to be the bridge between an experimental program and a computer modeling program. It is essential to corroborate experimental results with the numerical data that can be obtained from modeling. Flow modeling is prepared as an analytical study and would serve as the bridge between experiments and computational work.

Task Group II had diverse opinions as to what can be accomplished with numerical work. The need was seen for developing good turbulence models but there was a question as to how to handle the fine scale structure in the flow. For example, is it necessary to use the Navier-Stokes equations? To which level should grid scale resolution be pushed? What computational accuracy can be obtained? Is it 5%, 2%, or even better? Is it best to use a finite element or a finite difference approach?

All the above questions were addressed by our group, but conclusions were skirted because definite answers are not available. This result indicates the level of uncertainty associated with developing research plans and indicates the strong need for setting up research programs just for establishing the methodology to be used in full-scale computing studies.

Coordinate grid systems were viewed as being useful for helping the computations. In order for the computations to proceed more inexpensively, it was concluded as useful to look at the range of upstream and downstream conditions to see where there is an "infinity effect" so that the streamwise extent of the computational domain could be shortened. In considering that only a limited number of grid points can be scattered over the computation domain, a shorter streamwise distance between the upstream and downstream boundaries of the numerical scheme would produce a finer grid scale for resolving the small eddy details of the flow field. Task Group II also wished to see the computational work extended to large Reynolds number models. If all this were to be done, very useful information on the effects of these various items on the discharge coefficient would be obtained.

The Task Group was aware of the fact that numerical computations are not straightforward and require research on a long time scale. Because of the difficulty associated with this kind of research, alternative approaches were suggested. Some alternatives have already been discussed in the Friday morning presentation of results from Task Group I. Other simpler methods were also suggested, for example, to take a one dimensional, momentum integral approach.

It is my personal feeling that we should take a look at the orifice equation,

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x}$$

and the resulting correlation obtained from integrating between pressure taps:

$$\int_1^2 \frac{\partial V}{\partial t}\,dx + \frac{V_2^2(t) - V_1^2(t)}{2} = +\frac{p_1(t) - p_2(t)}{\rho}$$

This one-dimensional model would involve relating the dynamics of the flow as obtained experimentally to the dynamics of the results obtained from the computer and then relating both of these results to the behavior associated with an actual orifice plate in a metering situation. The final result could be a simple dynamic model for the flow through the orifice.

Subtopic 5. Computational Work.

Two and three dimensional numerical models were discussed. The state-of-the-art at this time allows for the calculation of reasonably simple two dimensional flow. Three dimensional flow is a difficult problem. The relationship between the two dimensional models currently being studied and the actual three dimensional situation existing in practice is not well understood and would also need to be considered as a research task.

Task Group II also addressed the need for treating unsteadiness in the flow. Problems currently studied generally start with some steady upstream conditions. The question of Reynolds number limits in computing also needs to be addressed. It is now possible to calculate a 1,000 or a 5,000 Reynolds number flow. The extent to which calculations can be extended to higher values needs to be determined. With current computational techniques, it should be possible to obtain the dynamics of the velocity and pressure fluctuations in orifice flow.

Should these tasks be completed, the next task would be to perform sensitivity analyses in which the discharge coefficient would be determined as a function of various design parameters taken singly or in combination.

The Task Group felt that it would like to have a computational competition similar to the "Stanford Olympics" for boundary layer flows that were held in the past. Using the philosophy behind the "Stanford Olympics", the task group proposed that some experiments should first be selected, performed, and suitable data bases obtained. A group of numerical modelers should then be asked to formulate their models for the purpose of predicting these experimental flows. The model solutions would use the experimentally observed boundary conditions determined from the experimental studies as the boundary

conditions for their computations. The details of the flow field to be specified by the computational models would be agreed upon in advance and each modeler would be expected to produce a numerical solution providing the required information. The experimental and modeling groups would then meet and exhange results in order to see which modeling techniques fit the data best.

If successful, this program would result in the development of a general computational tool validated by experiment for flows of interest. This achievement would fulfill an ultimate research goal. There were some in our group who insisted that this approach would never be successful, while others felt that it would eventually work, but that it will take considerable time. Somehow or other, the results of such a research program would have to be brought to standards committees to serve as input for the shaping of better standards.

Subtopic 6. Recommendations on Joint Efforts.

Task Group II suggested that experimental and analytical studies not be left to any single organization since there are a number of possible approaches to solving problems. Hence it helps to have a reasonable number of people working on the same problem. With these people and their groups interacting and collaborating on appropriate time schedules, it is felt that significant advances can be made.

Overview of Topics 2, 3, and 4.

Because most of the group's time and effort went into the discussion of the above described material on basic flow studies of incompressible flow, the group did not have sufficient time to give the same attention to the topics that follow.

Task Group II considered briefly several general problem areas. Steady and unsteady flow thresholds were considered important. Multi-phase flow was also considered, specifically as related to high quality wet steam measurement with orifice meters. The group discussed briefly the effects of compressibility on flow metering.

Topic 2. Pulsatile Flows and Dynamics of Secondary Systems.

The discussion of this topic began with the question of the determination of the threshold between steady and unsteady flow. It seemed that there were essentially two thresholds of concern. On the one hand, it is necessary to know the values of the various turbulence and noise parameters at which the flow ceases to be typical of fully developed turbulent pipe flow and, in particular, to study the manner in which the flow became atypical. It is necessary to know whether there is a significant effect due to the presence of a valve or some other kind of upstream fitting, or perhaps even to the presence of another type of flow meter. Another flow condition of considerable concern involves the presence of a regular cyclic pulsation in

the flow either superimposed externally or perhaps self induced by the flow such as might originate in the jet of the fluid passing through the orifice.

These two possible thresholds need considerable study. In worrying about them, one must be prepared for the possibility that there might be two separate effects, one due to the primary device itself, (i.e. the orifice plate) and the other effect due to the secondary devices (i.e. devices for measuring parameters such as pressure and temperature). Dealing with the secondary device could be difficult in view of the fact that such devices are not standardized in the context of flow metering. When looking at the primary and secondary devices, it becomes necessary to be concerned with four important items. These are:

(1) externally imposed flow noise or pulsation,
(2) self induced pulsation,
(3) the compressibility of the fluid and, finally,
(4) the effect on the flow meter of pipe vibration caused by flow pulsations.

It should be stressed here that these are not considered to be producers of very large errors. We are concerned here with very marginal pulsation or noise conditions. Nevertheless, it is necessary to know just when these conditions might become important.

Task Group II did not discuss and develop research projects for attacking these areas. These topics are simply put forth to invite comments on them even from our own task group members. Clearly if distinguishing between incompressible and compressible effects is of interest, it is necessary to do some work using liquids and gases. Thus, both water and air flow facilities would be necessary - each for a reasonable geometry, say using pipe at least three inches in diameter. It is necessary to be able to generate turbulence or noise in the flow as well as controlled pulsations artificially in order to look at their effects.

When looking at the effects of pulsation or noise on the secondary devices, it is absolutely essential to be able to measure the differential pressure very faithfully. It is necessary to be able to cover the full frequency spectrum of these effects. We believe this requires the development of twin flush mounted transducers for measuring the differential pressure. Any design which uses a single diaphragm connected to the pressure tappings by impulse lines is bound to have acoustic effects. The signal will therefore be corrupted above some limiting frequency.

To look at the flow itself requires the ability to measure the turbulent flow velocity at a point, such as with an anemometer, be it wire or film or, if sufficient funds are available, a laser Doppler velocimeter. In order to be able to analyze the resulting signals, spectrum analyzers and the usual range of ancillary equipment are needed.

The object of the experimental work would be to reduce the uncertainty in the discharge coefficient due to the presence of turbulence, noise, pulsation. An estimate of costs for a research program is given in Attachment 2.

Topic 3. Wet Steam and Gas Flows.

Task Group II also dealt briefly with two other projects related to multi-phase flow measurements and compressibility. Here, further thought is required to form estimates of the efforts needed. Flow standards currently state that orifices should be used only for a homogenous single phase fluid. What should be done in adapting these meters to two phase fluids? High quality wet steam measurement is very important in the process industry and hence we have to discuss this topic.

In order to learn how an orifice meter behaves in wet steam flow, it is necessary to study the flow field itself and to obtain information about the distribution of the water drops and the vapor, droplet sizes, their relative velocities, and other characteristics, both across the diameter of the pipeline and along the pipeline in the immediate vicinity upstream from the orifice. It is then necessary to study what happens when there are changes in pipe size, pipe inclination and pipe wall temperature (i.e. the effects due to imperfect insulation). Do these factors change the distribution of droplets in the pipe? This information must all be related to the flow-differential pressure relationship and everything else that must be measured in order to calculate the flow of the steam.

Returning to the topic of predicting the hardware required, one sees that a steam flow facility is, of course, essential. Regarding velocimetry for these small water droplets, the Task Group believes that a non-intrusive method like a laser Doppler or other kind of optical technique is needed. These systems have been used with some success. An estimate of resources needed for research in this area is given in the Attachment.

Topic 4. Compressible Flows.

Regarding the compressibility topic, Task Group II was unable to give this topic adequate discussion owing to time schedule. The limited discussion split this topic into two categories. The first category was uncertainty in the equations of state for gases and the second category had to do with the compressibility factors themselves. We would ask: "Does having a mixture of gases increase the uncertainty in these two categories?"

There are various empirical relationships for the equation of state giving different answers. These differences should be reconciled, but the group did not have sufficient time to reach even preliminary conclusions. It was felt that these questions are physics problems, and as a result, this topic should be separated from the second category which deals directly with the behavior of the flow meter in compressible flows.

The latter topics relate to questions dealt with earlier in the first part of the Task Group II report. We need to know what is happening downstream from the orifice plate, for example, and need to know the compressibility effects in the orifice jet and the eddy system behind the plate adjacent to the pipe

wall. We note that during the workshop's tour of the NBS Fluid Mechanics Laboratories, such an inherent unsteadiness was shown to exist even in incompressible orifice flow. Is this phenomena worse for compressible flows? We do not believe that this problem has been studied yet.

It is not clear to us how to estimate the needed hardware to study the effects in the physics category. Clearly, for the other category a gas flow facility, the usual laser Doppler equipment, spectrum analyzers, and related equipment, are needed. Estimates for manpower and equipment for a research program are given in the Attachment.

ATTACHMENT 1

Appendix to Task Group II Summary Report

Chairman's Summary Report
Task II Workshop Group
Orifice Flow Metering Workshop
National Bureau of Standards
June 9-10, 1983

The following is a summary of the deliberations of Task Group II in assessing the status of orifice flow metering in the area of basic flow research.

Attachment A illustrates the handout given to the participants on Friday morning, June 10, after the four task groups presented their preliminary reports to the entire assembly. The topics on Attachment A reflect the ideas discussed during the Thursday afternoon work session and the new inputs from the plenary session on Friday morning. The topics were discussed briefly and amplified during the work session. The participants were asked to indicate their preferences for further work in orifice flow metering.

A listing of the preferences of the group is provided in Attachment B. The legend and notes attached to these survey results explain the rating system used. Comments are offered below for each of the six topical areas identified on Attachment B. Please refer to the preceding discussion presented by the Task Group II chairmen at the plenary session on Friday morning for further amplification of these topics.

Topical Area 1: Experimental Work on Steady Incompressible Flows

The discussion sessions on Thursday and Friday did not devote much time to this topic. The participants seemed to agree that experimental work is necessary. The results in Attachment B indicate that most participants viewed work in the area of velocity profiles and the sensitivity of the orifice to changes in upstream flow conditions or installation effects to be most important. Detailed investigations of the structure of the flow coupled with flow visualization studies were also high priority items. Field measurements were given a relatively low priority ranking by comparison with the first topics mentioned.

In summary, the experimental work was deemed to be highly desirable.

Topical Area 2: Analytical/Computational Work on Steady Incompressible Flows

While the group was generally in agreement that numerical work would be of benefit to understanding the orifice flow metering problem, three distinct camps were joined by the participants. The first camp advanced the merits of computational techniques using the Navier-Stokes equations in a "first-principles" analysis. It was noted that unsteadiness as in turbulent flows would evolve naturally from the computations and the motion of turbulent

eddies would be shown by such a method. The work in this area is limited to low Reynolds number flows and is two-dimensional in nature.

The second camp favored the use of other computational methods as being more efficient and equally effective in predicting the flow field. This camp favored techniques such as turbulence modeling and the use of interaction methods or even simpler methods such as momentum integrals. These first two camps engaged in a lively discussion on this topical area.

The third camp had a more broad mixture of persons. The group was generally skeptical of the use of computational methods as a first priority in orifice flow research. Some members felt that more development of methods of computation would be required before large sums of funding should be given to further the goals of either of the first two camps. Many of the more experimental/practice-oriented members of the task group merely listened and used the discussion as an educational experience in this area of research. The third camp also advanced the chilling notion that two-dimensional computational studies may not be meaningful in the analysis of three dimensional flows.

The results of the survey on Friday morning, as shown in Attachment B, indicate that the group favors the use of modeling methods over the method of straightforward calculation of the flow using the Navier-Stokes equations. A greater emphasis was suggested in using the computational techniques to determine phenomenological effects on the flow patterns, as opposed to outright calculation of the entire flow field. The group felt that the focus in this area should be on determining accurate values for global parameters such as the discharge coefficient. The models could then be used to perform studies at minimal cost.

The overwhelming sentiment of the group was that the computational studies should be performed in conjunction with experimental programs of research. The idea of an "Olympics Program" was discussed and received mixed feelings from the group. Uniformly, it was felt that experimental work should be compared with analytical predictions, and vice-versa. Meetings during which information could be exchanged among those engaged in numerical computations, experimentalists, and practical metering engineers were also seen as desirable. However, the idea of having several groups performing duplicate experiments and several computer groups performing duplicate computations (using different methods) was viewed as too great a use of resources. (In other words, only one group should do either the experimental or numerical work and their results would be taken as gospel in that area). In view of the difficulties in getting agreement on values of discharge coefficient using the same meter in two different laboratories, this viewpoint of limiting the work to one group seemed highly questionable to those members of the task group who have been "burned" by erroneous results in the past.

In summary, the group felt that computational work would be of benefit, but the methods to be used to perform this work could not be agreed upon. The idea of a joint program of numerical and experimental work received a strong

endorsement along with the idea of informational meetings among researchers of different backgrounds and interests.

It is the sentiment of the Task Group chairman that the idea of an "Olympics Program" whereby many investigators attack a series of flow problems using their particular numerical models is highly desirable.

Topical Area 3: Non-Newtonian Flow Applications

This area of interest came to the forefront as a result of the Friday morning plenary session and was not discussed deeply in the Thursday session. Although it was pointed out that the orifice meter might behave differently for non-Newtonian fluids, the group as a whole generally gave this area of research a low priority for the present.

Topical Area 4: Wet Gas Metering

Originally, topical area 4 was broadly titled as multi-phase flow metering. However, the discussion both on Thursday and Friday generally pointed out the fallacy of using the orifice meter for flows for which it was ill-suited. Flows such as liquid/solid slurries or two phase gas/liquid flows such as low quality steam are cases where other alternative metering methods would be better suited. The focus on the multi-phase flow area was therefore limited to the metering of wet steam of high dryness fraction, or wet gases such as natural gas with a small amount of liquid droplets.

This area of research was not ranked as highly by camps (1) and (2) discussed earlier, but was given a higher ranking by the members of camp (3) who tended to be more practically oriented to the needs of gas flow metering.

Topical Area 5: Thermophysical Properties

Discussion in this area centered on the degree of accuracy which can be attained using equations of state to describe fluids where the state equations are in themselves not known to the accuracy desired of the orifice meter. The numerical computationalists in the group advanced the idea that calculations using compressible fluids present no problems. The focus shifted therefore to equations of state of fluids. The plenary discussion of Friday morning pointed out a series of research programs which are currently underway (see Attachment C submitted by Mr. Reintsema of Gasunie). The group agreed that recommendations for further work on thermophysical properties might be delayed until the results of these ongoing investigations are known.

The main questions on compressible flows and thermophysical properties focused on possible influences of fluid compressibility on the flow patterns, especially downstream from the orifice. The question of how unsteadiness might affect the flow of compressible fluids was also considered important.

This area of research received strong support from camp (3).

Topical Area 6: Unsteady Flows, Secondary Systems

It was noted that there is little data on pulsating flow at large Reynolds numbers as might apply to industrial systems. It was considered necessary to determine a threshold for unsteadiness which would separate a forced type of pulsation from excessively noisy turbulent flow. Characteristics of the secondary system which would be required to read-out these pressure pulsations would have to be identified. Problems of finding adequate instrumentation for dynamic pressure measurements were pointed out by the group and by the other participants in the plenary session on Friday morning.

The question of unsteady or pulsatile flow was given a relatively strong priority ranking, especially from the members of camp (3).

General Comments on Group Discussions

It was noted by members of camp (3) that some of the uncertainties in orifice flow metering evidenced by consideration of Topical Areas 4, 5, and 6 would be as large as the current uncertainties in the areas denoted by Topical Areas 1 and 2.

The overwhelming consensus of the group was that it had identified areas of interest and pointed out programs of research. Proposals in these areas would have to be judged on their own merit. The group therefore did not wish to prioritize any of the research areas identified above or get involved in identifying programs of study nor estimating the cost for such a program. This feeling probably came from the presence so many competing camps in our group that each camp (or one or more strong individuals within it) became concerned that the other camp (or individual) would be favored, for the record, if a vote were taken.

Topical Area 1 - Experimental Work on Steady Incompressible Flows

- Benefits
  - Develop an improved understanding of the physics of the flow near the orifice
  - Develop a data base for comparison and "proving" of numerical models
  - Determine the effect of upstream influences and orifice physical characteristics/specifications on the discharge coefficient
- Effort
  - To conduct the wide ranging test program described during the discussions is estimated to require approximately 20 man-years of effort (research personnel only).
- Cost
  - In view of the sophisticated instrumentation required to perform the experiments, an estimated cost is about $100,000 per man-year plus an additional $1,000,000 for instrumentation and data reduction.

Topical Task 2 - Analytical/Computational Work on Steady Incompressible Flows

- o Benefits
  - Develop computational techniques to the state where they can be used as a tool to evaluate the influences of various parameters on orifice performance
  - Can be used as a design tool for improving characteristics of orifices
  - Can be used to calibrate an orifice numerically as a function of actual installation conditions such as eccentricity, upstream flow conditioning, and other factors.

- o Effort
  - It is envisioned that turbulence modeling will be only as good as the models used in formulating the orifice problem. Initial success may be made in this area, but subsequent work will require more sophisticated models if the inaccuracy of the orifice under laboratory conditions is to be reduced to 0.1% level. The computational program will therefore require a series of efforts on different fronts.
  - Provisions should also be made for informational meetings and/or an "Olympics" type conference.
  - To complete the development of the orifice models and a wider range of computational studies will require approximately 18 man years of effort.

- o Cost
  - Estimate approximately $80,000 per man-year of effort plus $400,000 for computing expenses.

Topical Area 3 - Non-Newtonian Flow Applications

- o Benefit
  - Can be used by orifice meter manufacturers and users in general, but not so much for gas metering.
  - Probably would be used in chemical process industries.

- o Effort
  - A low level of effort is recommended of about 1 man year over a range of topics.

- o Cost
  - Estimate at $100,000

Topical Area 4 - Wet Gas Metering

- o Benefits
  - Will be useful in determining the actual BTU flowrate down the gas pipeline since liquid drops can contain a high energy level.
  - Will also have a wide range of applications in the metering of steam.

- Effort
  - Programs should be initiated to determine the occurrence of wet gas flows in pipelines and the means to sample accurately. These results can also be applied to the steam flow problem.
  - Approximately 5 man years of effort are recommended to identify problems and construct experimental apparatises for detailed studies.

- Cost
  - Experimental work could cost $500,000 for personnel and $200,000 for equipment. Analytical and literature work could cost $100,000.

Topical Area 5 - Thermophysical Properties

- Benefits
  - Currently the equations of state are not known accurately for metering purposes. Better accuracy could be obtained with better thermophysical property tables
  - Little is known about the behavior of compressible gases in an orifice flow field due to the absence of reliable instrumentation before the advent of the LDV systems. Experimental studies would help quantify the meter performance in these instances.

- Effort
  - The work on thermophysical properties has already been started (see Attachment C). Approximately one man year would be needed to monitor this area.
  - The experimental work would require approximately 2 man years for basic studies.

- Cost
  - The analytical work would require approximately $100,000 for evaluation of existing data and formulation of a more refined program of study.
  - The experimental work would require $200,000 for personnel and $300,000 for experiments.

Topical Area 6 - Unsteady Flows, Secondary Systems

- Benefits
  - Identify cases where pulsation and unsteadiness are important in flow meter applications
  - Develop better methods of obtaining data from secondary systems.

- Effort
  - Approximately 3 man years of effort on analytical studies and 5 man years of effort on experimental work.

- Cost
  - Approximately $600,000 for personnel and $300,000 for experimental studies.

Attachment A

Survey Form Distributed for Cross-Fertilization
Discussion of Task Group II on Friday June 10, 1983

- FLOW VISUALIZATION
- EXPERIMENTALLY DETERMINED VELOCITY PROFILES; PRESSURE MEASUREMENTS
- FLOW STRUCTURE: COHERENCE, CORRELATIONS
- SENSITIVITY OF ORIFICE PERFORMANCE TO CHANGES: INLET FLOW PROFILE, PIPE AND PLATE ROUGHNESS, EDGE SHARPNESS, ETC.
- FIELD MEASUREMENTS
- FLOW MODELS:
    - NAVIER-STOKES CALCULATIONS
    - TURBULENCE MODELS
    - INTERACTION METHODS
    - ANALYTICAL MODEL DEVELOPMENT
- COMPUTATIONAL VIEWPOINT:
    - FLOW FIELD COMPUTATION
    - PHENOMONOLOGICAL EFFECTS
- DESIGN PERFORMANCE STUDIES
- SENSITIVITY RESOLUTIONS - GLOBAL vs. LOCAL (COMPUTATIONAL)
- OLYMPICS PROGRAM
- INFORMATION EXCHANGE MEETINGS
- NON-NEWTONIAN FLOW APPLICATIONS
- WET GAS METERING:
    - ANALYTICAL
    - EXPERIMENTAL
- THERMOPHYSICAL PROPERTIES:
    - EXPANSION FACTORS EQUATION OF STATE
    - DENSITY AND COMPOSITION MEASUREMENTS
- SECONDARY SYSTEMS
    - INSTRUMENTATION DEVELOPMENT
    - ANALYSIS OF TRANSMISSION LINES

Attachment B

Task Group II Survey Results Friday, June 10, 1983
Cross-Fertilization Discussion

TOPIC	SCORES A - B - C	SCORES X - Y - Z	RANKING 1 - 2 - 3 - 4 - 5
1. Experimental Work			
Flow Visualization	9 - 4 - 1	9 - 2 - 1	5, 2, 0, 0, 1
Experimental Velocity Profiles, Pressure Measurements	13 - 4 - 0	12 - 3 - 0	9, 1, 1, 1, 0
Flow Structure, Coherence Correlations	9 - 6 - 2	8 - 5 - 2	4, 4, 1, 0, 1
Sensitivity to Changes in Profile, Roughness, etc.	14 - 5 - 0	8 - 6 - 0	4, 5, 3, 2, 2
Field Measurements	6 - 8 - 2	4 - 7 - 1	2, 2, 1, 1, 0
2. Analytical/Computational Work			
Flow Models:	6 - 5 - 1	4 - 2 - 0	2, 1, 0, 0, 1
Navier Stokes Computations	4 - 5 - 2	4 - 4 - 0	1, 0, 0, 0, 1
Turbulence Models	8 - 4 - 1	8 - 1 - 1	2, 1, 0, 0, 0
Interaction Methods	7 - 3 - 1	5 - 3 - 1	1, 1, 0, 0, 0
Analytical Model Develop.	3 - 3 - 2	3 - 1 - 4	1, 1, 0, 0, 0
Computational Viewpoint:	3 - 4 - 0	1 - 4 - 0	1, 1, 0, 0, 0
Focus on Flow Field Comp.	4 - 4 - 1	4 - 4 - 0	2, 1, 0, 0, 0
Focus on Phenomona. Effects	7 - 3 - 0	4 - 4 - 0	2, 0, 2, 1, 0
Design and Performance Studies	7 - 9 - 0	3 - 6 - 1	0, 3, 4, 1, 1
Sensitivity Studies to determine necessary Resolutions for Global Local Characteristics	8 - 5 - 0	2 - 4 - 3	2, 2, 2, 0, 0
Olympics Program to compare analytical methods with experimental data for selected flows	7 - 8 - 1	5 - 7 - 0	4, 2, 0, 0, 1
Informational Exchange Meetings	9 - 6 - 1	7 - 5 - 0	4, 1, 1, 1, 0
3. Non-Newtonian Flow Applications:	2 - 6 - 7	1 - 3 - 7	0, 2, 1, 1, 4
4. Wet Gas Metering:	6 - 6 - 3	5 - 1 - 5	2, 1, 2, 1, 3
Focus on Analytical Work	2 - 2 - 2	0 - 1 - 3	0, 0, 2, 0, 1
Focus on Experimental Work	3 - 2 - 1	1 - 1 - 2	0, 0, 2, 1, 0
5. Thermophysical Properties:	4 - 6 - 2	3 - 1 - 3	0, 3, 2, 1, 0
Expansion Factors Equation of state Effects on Flow Field	3 - 1 - 2	2 - 1 - 2	1, 0, 0, 0, 1
Measurement of Density and Composition	2 - 1 - 2	1 - 1 - 2	0, 0, 2, 0, 0
6. Unsteady Flow/Secondary Systems:	8 - 4 - 1	6 - 2 - 0	3, 2, 1, 2, 0
Instrumentation Development	1 - 3 - 1	1 - 2 - 1	0, 0, 2, 0, 0
Analysis of Transmission Lines and Secondary Elements	1 - 1 - 3	1 - 1 - 1	0, 0, 0, 0, 1

Legend

Ranking System A - B - C: Should we do research on the topic listed?

A - Research should definitely be done
B - The research is of interest; however, there are some questions about validity or usefulness
C - The research is not necessary

Ranking System X - Y - Z: When should we do the research cited in the topical area?

X - Do this research first (i.e., within the next three years)
Y - Plan to do this research in future years (more than three years from now); resources are limited
Z - Decide whether or not to do the research after the results of other studies are analyzed

Ranking system 1 - 2 - 3 - 4 - 5: Priority preference for selection of research to be done

Using (1) to denote highest priority, rank topics in order of importance. Assign rankings no higher than fifth priority (5) to narrow number of choices.

Notes

Numbers for scores in the ABC and XYZ ranking system denote the number of votes for A, B, C, respectively, and XYZ, respectively.

Numbers under the 12345 ranking system denote the number of votes for first priority, second priority, etc., respectively.

There were 20 ballots returned by the participants. (Session officers did not vote). Not all ballots had marks in all categories, in which case, some topics received fewer votes than others.

Some participants used (5) to denote a fifth ranking priority. Others used (5) to denote a last priority. Some participants ranked many topics as (1). It is best to use the total number of votes cast for a particular topic as on indication of the interest of the participants in that topic.

A typical ballot would have the most categories rated under the ABC ranking system with the least amount of ranking information given for the 12345 Ranking System.

Attachment C

Compressibility Factor Research
submitted by
Dr. S. Reintsema
Gasunie, The Netherlands

1. Europe
Coordinated by GERG (European Gas Research Group), with member transmission companies working on it.

Gasunie (NL)
British Gas (UK)
Ruhrgas (W. Germany)
Gaz de France (F)

Reports have been given at:

- o the IGU Conference, Lausanne, 1982
- o the IGRC Conference (only by Gasunie), London, 1983

The program is to be completed in 1984.
The range of interest is the custody transfer region:

0 - 40°C
0 - 80°bar

Natural gas composition:
50-100% C_1, 0-20% C_2, 0-5% C_3, 0-30% CO_2, 0-50% N_2

2. U.S.A.
GRI - sponsored research at University of Oklahoma, Norman, OK, principal investigator Professor Kenneth E. Starling.
Scope of Work: -200 to +400 °F, 0 to 20,000 psi dry natural gas
Accuracy aimed at: in custody transfer region: 0.2%.

Project will be completed June, 1984.

TASK GROUP III

MEASUREMENT PROBLEMS ASSOCIATED WITH ACTUAL METERING CONDITIONS AND POTENTIAL SOLUTIONS

Chairman, H. H. Dijstelbergen
Ministry of Energy
Wellington, New Zealand

Vice Chairman, M. L. Williams
Amoco Production Co.
Houston, Texas

This Task Group was charged with looking at metering problems and suggesting the research projects needed to solve them from the point of view of practically experienced difficulties. An important first conclusion reached on examination of the impediments which stand in the way of increasing the accuracy of orifice plate measurement was that the problem originates from two elements. Firstly, the primary element, i.e. the orifice plate, its tappings, etc. and, secondly, the secondary elements i.e. pressure transducer, thermometer, etc. with the secondary elements contributing in practice a very large part, even as much as half, of the uncertainty.

It was felt, specifically, that the differential pressure transducers are still inadequate, even though they have been improved considerably over the last few decades. In particular, because of their temperature dependence, they contribute quite substantially to the uncertainty of the flow measurement in a practical situation. These transducers also affect the practical rangeability of an orifice plate meter. Practical rangeability is perhaps one in three for reasonable uncertainty. A rangeability on the order of one in ten would be preferable. That would, of course, demand pressure differential transducers of a much higher quality than are currently available. The Group considered this problem to be mainly outside the scope of this workshop since the focus here is on the primary element. Thus, although the Group did not formulate a research project dealing with secondary devices, it should be kept in mind that secondary instrumentation does indeed contribute substantially to the overall metering uncertainty.

The Group discussed the problems in its assigned area of concern from the point of view of the specific difficulties encountered in designing, building and operating an orifice meter installation. Thus, suppose it is desired to measure the flow of fluid within a pipe from some point A to some point B. These points might be in an existing installation and, in fact, there might already be piping between those points in that installation. It becomes first necessary to design a metering station; second to manufacture the meter and its associated components; third to operate the completed facility including, perhaps, field checking of the system; and, possibly, individually calibrating the orifice meter.

The Group's discussions were wide-ranging and the chairman and co-chairman have attempted to distill these and to formulate research projects based on them. The chairman believes that the projects he is proposing contain most of the items discussed by the Group. Also included are estimates of the priorities which the Group appeared to put on these projects.

Project 1: Resolution of differences between standards regarding requirements for straight lengths.

The item given the highest priority is the resolution of the differences between the two basic standards. Thus, there is, on the one hand, the ISO/ASME standard and, on the other hand, the AGA/ANSI standard and these are in disagreement. The fact that there are two standards is quite embarrassing to the industry. The specific difficulty which was of most importance to the Group is the required length of straight pipe upstream of the meter which differs for the two standards. In fact, the issue of the upstream length was felt to be even more important than that of studying the discharge coefficient itself. The Task Group members were not aware of any effort being made in the United States to resolve this problem. It was concluded that it must be attacked as soon as possible. These efforts would, of course, have to be coordinated with the work which is being carried out at present in the EEC.

The research project needed would involve an investigation of the influence of upstream straight lengths on the discharge coefficient, coordinating this research with the efforts currently underway. Part of the equipment currently being used in the United States for the discharge coefficient tests could be used for this. It is estimated that the project would require approximately two man years and could be finished in two calendar years. An estimate of the cost is interesting but difficult without detailing the project. Generally labor costs in New Zealand are quite low, and the chairman felt that his estimates might therefore be low. According to his experience in estimating the cost of research in any currency, even a very carefully made estimate of research cost must subsequently be multiplied by roughly 2.2. A result is then obtained which is close to the level of resources actually found to be needed. His cost estimate for this task comes to over $300,000. The benefits obtained would be the development of one generally accepted international standard. The project should be sponsored by the same bodies as are sponsoring the coefficient programs and the results would ultimately be transmitted to the respective standard bodies involved.

Project 2: Measurements with non-standard installations

The second problem discussed by the group, was the influence of deviations from the standard in the design. In practice there may be many reasons why it is almost impossible to keep to the standards. Ideally, the designer should have an indication of the direction and magnitude of the coefficient changes for a given deviation from the standard as well as an estimate of the resulting increase in the measurement uncertainty. Several parameters associated with an installation which might, in practice, be found to deviate from standard values were discussed. In the first place, of course, the

influence of non-standard straight lengths was discussed. This ties in with the project already mentioned. Further items include the influences of deviations from standard values-pipe roughness, pipe out-of-roundness, eccentricity, orifice edge sharpness and, finally, of the buckling and bending of orifice plates. The Group felt that there was already an extensive literature on this subject mostly in English and German and some in French. It was felt that the best approach to such research would be to start with a literature survey, collecting all the available data. The Group felt that there is much more in the literature than most people realize. The older standards, the present German "work sheets" (codes of practice) and the former British standard contain procedures which are admittedly insufficient. Nevertheless they gave indications as to what could be expected to happen if a design moved off from the design point set by the standards. These indications were based on experiments which in many cases have been reported separately. Thus, much might be learned for some of these problems simply by collecting such information as is already available.

The title of such a project might be "non-standard installation effects." The practical need arises when, in many industrial applications, it is too costly (and often unnecessary) to meet the requirements established for obtaining highest accuracies. For example, it is common for there not to be sufficient space available to accomodate the required straight length. Yet it is not at present possible, in most cases, to estimate the loss of accuracy which is associated with specific deviations from the standard. Thus it is not possible to produce a cost benefit analysis in terms of increased metering error associated with not fully adhering to the standards. As already mentioned, the project would start with a thorough search of the available literature. This could be carried out by one graduate student working perhaps half time for two years. It would be highly desireable for him to have at least a working knowledge of German. The cost for this phase could be less than $30,000. Benefits would include savings to the process industry and a better quantitative understanding of the effects of the deviations from the situation described in the standards. The study should be undertaken by or under auspices of flow laboratories and interested bodies. This should lead to a report to national and international standard organizations which would then serve as the basis for a standard along the lines of the German standard DIN 2040 or the former British standards. One book giving some indication of current practice and which was used extensively in the past is the Shell Flowmeter Hand-book. Unfortunately, it is no longer being reprinted.

Project 3: Edge sharpness and eccentricity

Two subjects already mentioned, and which the Group thought warrant further investigation, are edge sharpness and orifice eccentricity. It is our feeling that, for these subjects as well, the best way to start this as well is by first surveying the literature. A great deal has been published on these two subjects, especially on the effects of the rounding of the edges. On the basis of the existing literature, one can probably design experiments, which can involve either experiment or theory (based on models) and which can be correlated with some practical tests. A problem which needs first to be faced

concerns the present methods of measuring orifice edge sharpness. Such methods are either very inaccurate, (for example, the visual method which can hardly be called a measuring method) or are time consuming. Nevertheless, even if the edge sharpness could be accurately measured one still does not know the effect on the uncertainty of a slightly blurred edge or a blunt edge. It was felt, however, that a fast and easy method of measuring the sharpness needed to be developed.

Similar remarks hold for eccentricity. The effect of slight eccentricities can best be established by first studying the literature. There is certainly not a standard which gives a reliable estimate of the effect of a slight eccentricity on the flow coefficient. In the new ISO standard there is a problem with eccentricity since the restriction on eccentricity is very hard to meet especially for high beta ratios and small diameters. The requirements are based on experiments on larger diameter pipe. The requirements on the eccentricity are, in fact, higher than are the requirements on the out-of-roundness of the pipe, and hence cannot even be measured. It is therefore absolutely essential that the eccentricity effect be further investigated to see if it is possible to establish standards which are less stringent than the current standard especially for the smallest diameters. If the requirements cannot be relaxed it becomes necessary to know by what amount the flow measurement uncertainty has to be increased. This effort could be completed by any well equipped flow lab and the results submitted to the standards bodies.

The research project required would be aimed at determining the increase in the uncertainty of measurement due to edge bluntness and eccentricity. The project would first incorporate a survey of the international literature. The data obtained from this literature search could be used as a basis for theoretical studies which would then be correlated with the practical tests. The first part of the project, i.e. the literature survey could probably be done with half a man year of effort by a graduate student and would cost about $15,000. The second part might need $200,000 or perhaps two men for 2 years. The total time required for the total effort might be approximately 3 years. There is also a need for comparing present quantitative measurement methods for the orifice edge sharpness. Theories on the effect of edge sharpness are useless if that sharpness cannot be measured. No practical correlation is then possible. Comparisons should be made between the lead foil, casting and optical methods. There is also a method which uses a kind of Talysurf and is used with the plate set at 45° to a stylus which rides up and over the sharp edge. It is essential to compare the results of these various methods to see if they give the same measure of edge sharpness and to see if one of them might be easier to use than the others.

The cost of the investigation of the edge sharpness measurement methods would not be high. It could be done in approximately 1/2 a year by a graduate student working perhaps half time. Thus, only a quarter of a man year might be needed. Apart from the equipment cost, which is difficult to estimate, the cost would be only approximately $10,000. The benefits which would follow

from the total project would include an ability to estimate the uncertainty which followed from deviations from extreme sharpness. This would generally assist in the commissioning of new installations as well as in the field check of existing installations.

Project 4: The nature and origin of fluctuations in the differential pressure

The last project discussed by the Group concerns unsteady differential pressure measurements and hence ties in with the mandate of Task Group II. The problem was formulated in terms of unsteady differential pressure because that is what is observed. In fact, such behavior is observed even with a flow which is as steady as possible. The existence of this unsteady pressure differential has caused many problems in orifice meter practice for as long as the standards have existed. The influence of unsteady flow has been an item of research interest for over 30 years. Researchers have attempted to attack the problem but with little success. It is indeed a basic operational problem. In the chairman's opinion, this unsteady differential pressure results either from the fundamental properties of the flow phenomena in the vicinity of the orifice plate, in the manner described for us in the overview talks during the last day and a half, or stems from unsteady conditions which originate upstream of the orifice plate. It would be useful to determine if there are advantages in the use of certain tapping configurations in preference to others as a means to minimize the effect of this unsteadiness. It would also be interesting and useful to know if flow straighteners can have an effect on these phenomena, and, if so, how much.

Finally, not only are the amplitudes of these fluctuations interesting but so also are their frequency spectra. It has been observed in some experiments that the measured orifice plate coefficient shows a slow apparent variation with time. Yet, when averages over a day are compared, a steady value is obtained. A very good correlation is, in fact, obtained between the long-term average values for two orifice plates measuring the same flow. If, on the other hand, the difference between such a pair of plates is followed over a period of an hour or half an hour, the correlation between them becomes quite bad. This phenomenon has been observed quite often both in the field and under laboratory conditions. Thus, it is especially necessary to look at the low end of the frequency spectrum.

This work could lead to an ability to characterize steady flow or, perhaps better, to a characterization of the fluctuations. It might then be possible to establish a threshold which would distinguish between the need for an analysis based on steady flow phenomena and that needed for analyzing unsteady flow. Of course, it is presently not desirable to require the use of very sophisticated measuring equipment in the field. All that is available at a metering site are the pressure tappings on the pipe. It would, for example, not be desirable at this time to require laser Doppler anemometry measurements on a routine basis in a practical installation. It seems then, that the result of this kind of research must be the development of a method of interpreting fluctuations in pressure differential signals and, furthermore, of the optimization of the pressure tap configuration and location with

respect to these fluctuations. The pressure differential for steady flow would need to be time analyzed with and without different flow straighteners installed upstream of the meter down to very low frequencies. The experiment would need to include measurements of differential pressure taken at different tapping configurations.

Another aspect of the metering problem which came up in the discussion dealt with the difficulty in making distinctions within the uncertainty calculations of orifice plates. Thus, there is no way to distinguish between a part of the uncertainty which is random in time and one that is systematic in time but random over a number of plates or installations. The systematic uncertainty consists itself of a part which is due to the particular realization of the installation (so due to manufacturing tolerances, etc.) and a part which is inherent to the design and calculations as given by the standard.

The problem makes itself felt when measuring large flow rates by several orifice plate meters in parallel. In that case not only fluctuations in time are averaged but so also are the uncertainties in geometry. The uncertainties in the coefficient due to the standard will not average out, however. The problem could be studied by experimenting with a number of similar orifice plate meters in series. Time averaging would yield the difference due to the individual geometries. Comparison with a standard reference would give an indication of the uncertainty bias of the coefficient as calculated for this design. It could also lead to a preferred set of tappings for producing a minimum amount of noise in the system.

In summary, the problem of unsteady pressure signals is ubiquitous. No orifice plate meter generates a steady pressure differential. Part of this is due to intrinsic phenomena in the vicinity of the orifice plate itself and part due to the upstream flow not being steady. The goal of the research project would be to produce enough of an understanding to allow for the characterization, for steady flow, of the variations in differential pressure both in amplitude and frequency distribution. The research would attempt to distinguish between variations associated with normal fluctuations in steady flow and variations due to unsteady flow.

It seemed to the Group that one graduate student, working full time, might complete this in two years. The required financing might be $100,000. Benefits would be the development of a first step toward the characterization of steady flow and might possibly explain some of the observed apparent changes in the discharge coefficient. It might also help divide the total metering uncertainty into random and systematic components and might lead, as well, to a means for designing preferred tappings on the basis of minimum noise production.

The research would need to be carried out by an organization which has expertise in both flow measurement and signal analysis. Results would need to be disseminated in papers at conferences and reports and eventually, incorporated in standards.

TASK GROUP IV

ORIFICE CALIBRATION, STANDARDS AND TRACEABILITY UNDER LABORATORY AND FIELD CONDITIONS

Chairman, G. Less
National Gas Pipeline Co.
Chicago, IL

Vice Chairman, J. A. Brennan
National Bureau of Standards
Boulder, CO

This Task Group was charged with developing research efforts for improving orifice calibration standards and traceability under both laboratory and field conditions. The Group had extensive and very good discussions but ran out of time before completing the assigned task. The Group discussed some subjects which overlapped the topics assigned to other task groups and this was good. One such topic, in particular, was upstream flow conditioning. Another was a need for producing agreement between ISO 5167 and the AGA Report #3 (and the ANSI Standard and API Manual as well). This was covered by another Task Group report and so it will not be necessary to dwell on it here. The Group also felt certain standards in ISO 5167 to be too tight.

The research projects which the Group developed were mainly in the area of interlaboratory comparisons. The problem relates to our not knowing sufficiently well how different laboratories compare to each other. This makes it impossible to keep them under statistical control as a group. It will be necessary to look at the entire measurement process thereby revealing any bias that might exist in a particular laboratory. It would be necessary to determine the calibration capabilities of the various laboratories in some detail and to improve these capabilities where needed. This, in a nut shell, is the aim. To do this requires that there be available meters with stability, high resolution, repeatability and, if possible, which can be used in a variety of media. Only then can meaningful intercomparisons be made. Such meters may be hard to find or develop.

Dr. Mattingly presented a brief description of the Youden statistical method for determining the extent of differences between laboratories. Any intercomparison program must be built around this kind of statistical approach. Personnel required are essentially those involved in the measurement of flow at the various laboratories. The time scale required depends on the number of laboratories which would participate. Cost is hard to estimate but the Group felt that the program would probably be quite expensive.

A drawback of this particular approach has to do with its long time scale. This has been attempted in the past with other meters and the resulting round robin of measurements always needed a very long time. This means that, in order for such an approach to succeed, each laboratory would have to agree to

participate in the program on a continuing basis over a long period of time with the work following a regular round-robin schedule. Yet there is no choice other than to carry out such a program since otherwise sufficient confidence cannot be built up in all of the laboratories. In order for this to be successful, it would be necessary for one particular individual to have the responsibility for scheduling the round robin. All data which would result from this effort must then be made immediately available to all interested parties.

The Group also considered the determination of compressibility values for sonic nozzles for natural gas as a possible research item. Sonic venturi nozzles have been used in the space industry with great success and they are now beginning to be used in natural gas applications. There are problems with such nozzles, however, especially as regards the need to develop better compressibility values. Nevertheless, these meters are already excellent measuring devices and the chairman reported that his company has proven this to its own satisfaction, in fact using them for calibrating turbine meters. Part of the API/GRI program aimed at producing a revision of the orifice coefficients in AGA Report #3 (or ANSI 2530) includes a plan to run sonic venturi nozzle tests at the test facility associated with the chairman's company in Joliet, Illinois. The purpose of this work will be to define the discharge coefficient at higher Reynolds numbers. At the water calibration facility in Gaithersburg, it is only possible to develop discharge coefficients in a very narrow band of Reynolds numbers. It is necessary to extend this range and sonic nozzles appear to be good devices for doing this. The Joliet part of the project will also extend the gas work ongoing at NBS Boulder.

Compressibilities currently available for sonic nozzles are based on some tables that were developed by Johnson in the early 1970's using an appropriate model. Improved compressibility values are needed. It might also be necessary to develop some hardware for measuring the velocity of sound experimentally. Such measurements would have other uses. They are, for example, needed to verify the calculations of compressibility values for mixed gases such as will come out of the GRI supercompressibility project.

The benefits for this work have already been stated and a rough estimate of cost can be given. It would be at least $100,000. The best way to implement this project would be to obtain the expertise of someone who is knowledgeable in sound velocities. There are people available who are capable of this. The organization running such a project could be any qualified organization and the data once developed must be disseminated to all interested parties.

GRAND BALLOT RESULTS

E. A. Spencer
G. E. Mattingly
M. Klein

In order to be able to assess the perceptions of the workshop attendees as to the relative importance to the improvement of orifice metering practice of the various research topics as put forth by the task groups, a survey of all attendees was conducted at the final session of the workshop. Eighteen (18) items (research projects) suggested by the task groups were identified by brief descriptions on ballot forms and all attendees present in the final session were invited to rank them according to priority, see Fig. 1. The chairman, in response to discussion, suggested that attendees put particular emphasis on the identification of six ballot items of highest priority. Fifty-eight (58) attendees completed and returned their ballots. The criterion to be used was given as " ... the importance of the topic to improving orifice metering."

The results of this survey are presented graphically in Figure 2. These histograms show the distributions of the top ten (10) votes received from each voter for each of the eighteen topics. The placings of the items were then analyzed by considering those which were the top six (6) according to the number of votes (i.e., the top third of the eighteen topics) and by ranking the individual topics according to vote totals. The ranking results are presented in Figure 1, column A. These show that the topic considered most important, at least in the sense of a consensus, is number 14:

> "An assessment of the amplitude and frequency characteristics of the instantaneous differential pressure in normal, steady flow conditions with the aims of:
>
> i) defining the steady/unsteady flow threshold,
>
> ii) improving differential pressure measurement."

Next in importance to this topic, and not far behind in the number of votes, is number 16:

> "The continuation of routine interlaboratory comparisons for the purpose of cross-checking estimated accuracies of the calibration facilities."

Next in importance, and considered essentially equal in rank by these voters, are topics numbered 2, 3, 7, 8, and 13. Thus, the top one-third of the research issues brought forth and discussed by workshop attendees reflect a broad range of concerns and experience. This range reflects the practical aspects of determining accurate differential pressure measurements from orifice meters and assessing calibration facilities using round robin techniques.

Task Group	Project No.	Title/Description	A Total/Rank	B Total/Rank	C Sum/Rank
No. 1 Upstream Flow and It's Effects on Orifice Metering	1.	Survey of literature on upstream flow disturbances and their attenuation.	21	20	41
	2.	Survey of industrial practice to identify the ten most commonly occurring upstream pipe fitttings and configurations.	23 3*	21	44
	3.	An investigation of the sensitivity of orifice performance to changes in the upstream flow conditions using computer prediction and experimental testing for different types of tappings and beta values.	23 3	31	59 2
	4.	The computer aided design of low loss straighteners to generate predictable flow conditions.	14	13	27
	5.	Development of a flow conditioner/orifice package which would give predictable discharge coefficients irrespective of upstream conditions.	18	37 1	45 2
	6.	Creation of a catalogue of correction factors to compensate for the effects of the most common disturbances.	7	10	17
No. 2 Fluid Flow Phenomena in Orifice Meters	7.	A study of incompressible flow patterns through orifice geometries using experimental techniques and computer modeling.	23 3	26 6	49 6
	8.	A study of unsteady flows with the objects of defining the thresholds between: i) "steady" and excessively noisy flows; ii) "steady" and pulsating flow; paying particular attention to the secondary system dynamics.	23 3	20	43
	9.	An investigation of compressibility effects in the flow patterns through orifice geometries with particular attention to the inherent unsteadiness due to coherent structures generated in the jet flow downstream of the orifice plate.	13	16	31
	10.	A study of the effects of small mass fractions (liquid/gas) of moisture in gases and vapors on orifice metering accuracy.	3	15	18

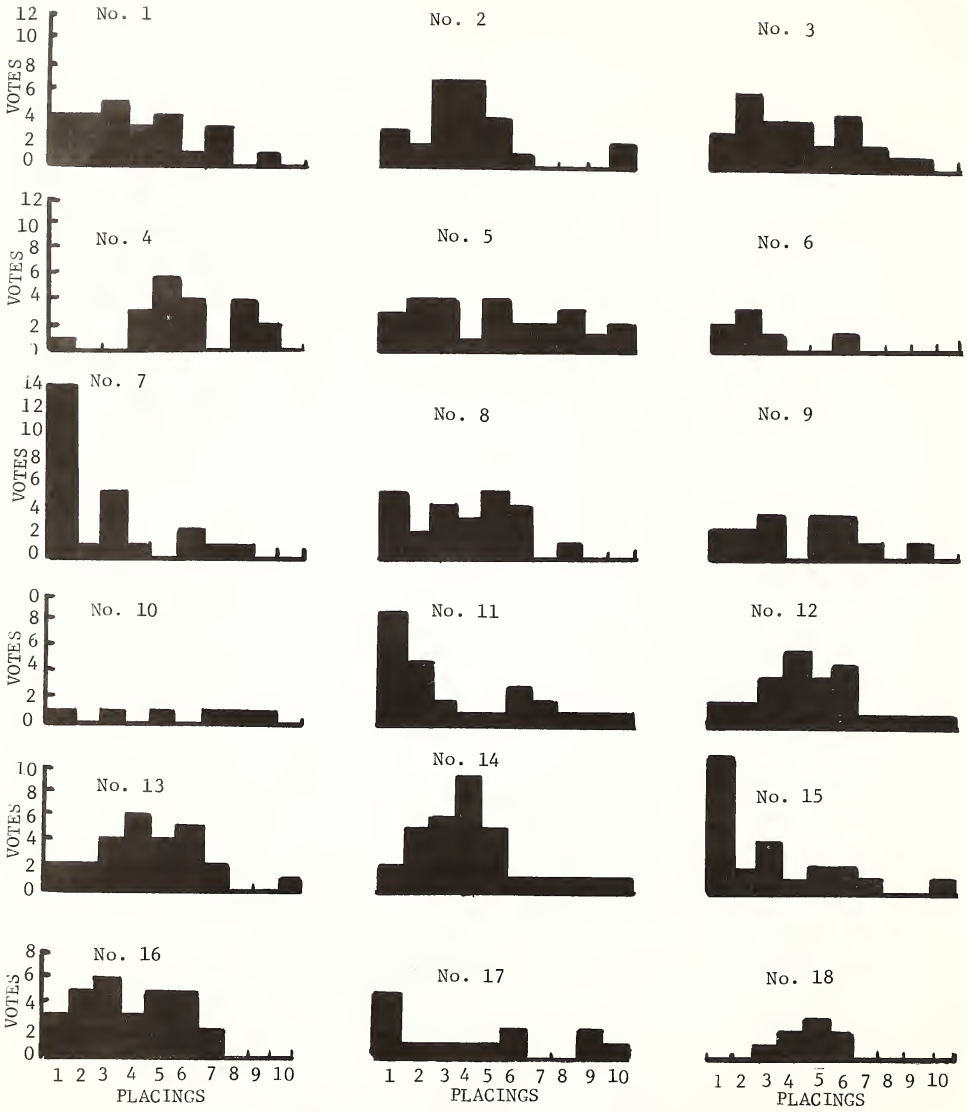
*This denotes equal rank with other entries similarly marked.

Figure 1. GRAND BALLOT RESULTS

Task Group	Project No.	Title/Description	A Total/Rank	B Total/Rank	C Sum/Rank
No. 3 Practical Orifice Procedures and Potential Solutions	11.	Tests to resolve different requirements for upstream straight lengths given in ISO/ASME and AGA/ANSI standards.	21	33 2	54 4
	12.	An analysis of the existing published data concerning the changes and increased uncertainty in the discharge coefficients associated with deviations from the specifications and installation conditions laid down in the standards.	13	23	36
	13.	A study of the problems associated with measuring edge sharpness and eccentricity and theoretical and experimental studies on their effects on discharge coefficients.	23 3	28 4	51 5
	14.	An assessment of the amplitude and frequency characteristics of the instantaneous differential pressure in normal steady flow conditions with the aims of: i) defining the steady/unsteady flow threshold; ii) improving differential pressure measurement.	28 1	27 5	55 1
No. 4 Calibrations, Standards, and Traceability in Lab	15.	A program to determine thermodynamic data for real gas effects as applied to orifice meters and critical flow venturis using air and natural gas mixtures.	22	21	43
	16.	The continuation of routine interlaboratory comparisons for the purpose of cross-checking estimated accuracies of the calibration facilities.	27 2	21	48
	17.	A feasiblity study of designing an in-situ proving device for gas flow meters.	13	14	25
	18.	The assembly of a data base to facilitate the comparison of critical flow venturis and orifice plates for the measurement of high pressure gas.	8	10	18

*This denotes equal rank with other entries similarly marked.

Figure 1. Grand Ballot Results



FIRST TEN PLACINGS OF THE EIGHTEEN TOPICS
FIRST BALLOT

FIGURE 2

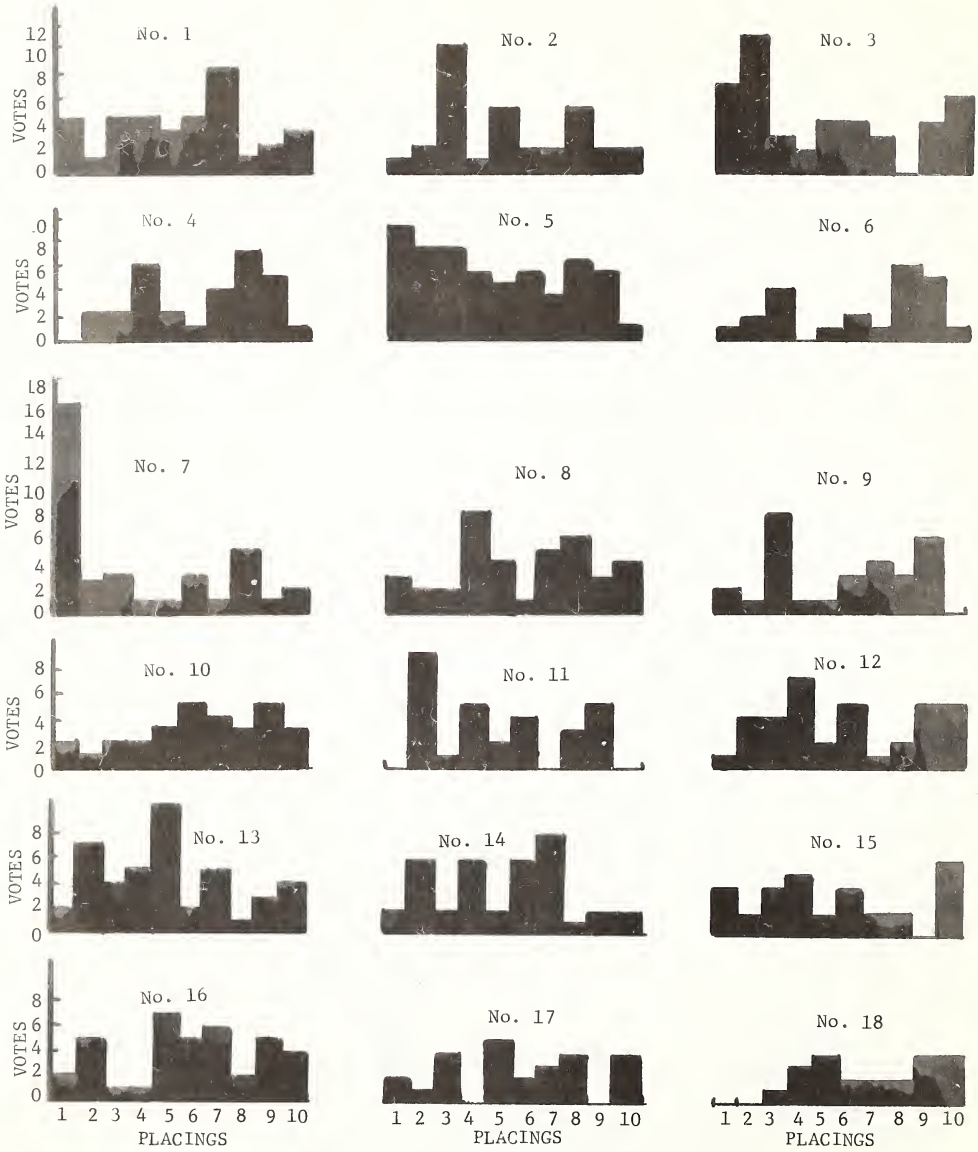
It is also noted that there is considerable interest in applying the fluid dynamic research tools now available for this purpose - computer modeling and experimental techniques - to four (4) of the top seven (7) topics or areas of concern. These areas are: upstream flows and their effects on downstream meters, fluid flow phenomena within the meter geometry, "steady and noisy" flow as well as "steady and pulsating" flow, and the effects on meter performance of orifice plate sharpness and eccentricity. Related to these concerns for the effects of variation in upstream flow profile is a voter interest in surveying industrial metering installations to determine common features.

Because only fifty-eight (58) of the total of one hundred (100) workshop attendees were present and voting at the final session, it was decided by the three organizers to mail a ballot to the attendees requesting a repeat prioritization as of several weeks later. The same criteria were used as in the first ballot. It was felt by the organizers that this would have the potential for acquiring the perceptions of a larger percentage of the attendees. It would also indicate effects from an intervening time and, hence, from the perspective gained in reflecting on these orifice issues and from reaction to the workshop as a whole. There would also be an effect in this new ballot due to the respondents having returned to their normal working environments.

The letter requesting this second prioritization produced an increased response to sixty-nine (69) ballots. These voting results are shown in Fig. 3. They altered the original ranking in several ways but in many respects left certain issues unchanged in perceived importance. When these results are processed in exactly the same way as was done for the first ballot, the rankings produced are as shown in Figure 1, column B.

The topic now considered most important to improved orifice practice is the development of a flow conditioner - orifice meter package which could give predictable orifice coefficients regardless of upstream conditions. Next in importance is a closely related topic, No. 11 which concerns the differences in the specifications for upstream piping lengths in international paper standards. Topic No. 2 is now ranked third as in the previous ballot. Thus it is concluded that the top three concerns ranked important by workshop attendees pertain to the upstream fluid flow profiles entering the orifice meter. Fourth in importance are concerns for the measurements of orifice plate sharpness and eccentricity and their effects on meter performance - i.e., discharge coefficient.

The topic previously considered most important in the first ballot, No. 14, was found to rank fifth. This shift was not found to be due to a decrease in the number or distribution in the number of votes the topic received. It appeared to result chiefly from the fact that four other topics are now considered to be more important than they were at the first ballot. One can



FIRST TEN PLACINGS OF THE EIGHTEEN TOPICS
SECOND BALLOT

FIGURE 3

only speculate as to the reasons for this - perhaps the increased number of ballots or perhaps the intervening period has sharply focused attendee concern on the importance of research efforts to characterize the fluid flow phenomena both in the upstream piping as well as inside the meter, e.g., and that produced by edge sharpness and plate eccentricity variations.

The sixth most important topic emerging from the second ballot is No. 7. This change in ranking was due to the additional votes received as compared to those cast for the topics earlier and originally ranked equal with it. This concern for:

> "... flow field studies inside the meter geometry using experimental techniques and computer modeling."

agrees with the above assessment of second ballot results reflecting a prevailing concern for improving the understanding of the flow phenomena which form the fundamental basis of orifice performance. Furthermore, it is noted that topic No. 7 did receive the highest number of votes in both ballots as the topic considered "most important" by the attendees.

The results of the voting for the two ballots have been combined by summing to produce the final tallies shown in Figure 1, column C. This combined result does not alter the top six topics ranked in the second ballot. It does reorder them, however, and in this regard the combined results may be thought misleading in expressing current opinions on the part of workshop attendees as to the ordered importance of these ranked topics to the improvement of orifice practice.

Therefore, it seems quite apparent that, judging from these expressions of attendee perceptions, there is an overwhelming concern that there is a great deal that is currently unknown about the fluid flow phenomena that control orifice performance. To achieve the needed understanding of these fluid phenomena, both of the rankings indicate that research efforts should be conducted on the flow effects produced by the upstream piping. The doubling in the second ballot of the votes cast for the effort:

> "... to produce a flow conditioner-orifice package whose performance cannot be perturbed by upstream conditions..."

and the significant increase in votes cast for

> "... resolving differences in orifice installation specifications..."

clearly expresses this concern. The votes cast for

> "... studies using theoretical and experimental techniques, on the effects of orifice edge sharpness and plate eccentricity on discharge coefficients..."

further reflect this.

The remaining topics in the top six specifically refer to the application of experimental techniques and computer modeling efforts to characterize the fluid dynamical phenomena that are the fundamental bases of orifice performance.

The mandate seems clear: a range of research results are needed for improving orifice metering performance. Appropriate research projects can now be proposed to produce the needed results. The sooner funding can be secured from appropriate sources to enable these projects to get started, the sooner improved orifice performance can be expected.

LIST OF ATTENDEES
GRI-NEL/UK-NBS
WORKSHOP ON FUNDAMENTAL RESEARCH ISSUES IN ORIFICE METERING
NBS-GAITHERSBURG, MD
JUNE 9-10, 1983

Mr. Herbert S. Arnold, Jr.
Public Service Electric & Gas Co.
80 Park Plaza (16A)
Newark, NJ 07932

Mr. M. Ashmawey
National Bureau of Standards
Fluid Mechanics Bldg.
Washington, D. C. 20234

Prof. R. A. Bajura
Dept. of Mechanical & Aero Eng.
West Virginia University
Morgantown, WV 26506

Prof. R. C. Baker
Fluid Eng. Unit
Cranfield Inst. of Tech.
Cranfield Bedford MK430AL
UNITED KINGDOM

Prof. Robert Balmer
Dept. of Mech Engineering
Univ. of Wisconsin-Milwaukee
Milwaukee, WI

Prof. C. Bates
Dept. of Mech. Engineering
and Energy Studies
University College - Newport Road
Cardiff CF1
Wales
UNITED KINGDOM

Prof. S. R. Beitler
Ohio State University
Dept. of Mech. Eng.
206 W. 13th Avenue
Columbus, OH 43210

Mr. H. Bellinga
NV Nederlandse Gasunie
Post Bus No. 19
9700 MA Groningen,
THE NETHERLANDS

Mr. K. R. Benson
National Bureau of Standards
Building 230
Washington, D.C. 20234

Prof. S. Berger
Dept. of Mech. Eng.
Univ. of Calif-Berkeley
Berkely, CA 94270

Prof. P. Bernard
Dept. of Mech. Eng.
Univ. of Maryland
College Park, MD 20742

Dr. Samuel Bernstein
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631

Mr. J. Brennan
National Bureau of Standards
325 Broadway
Boulder, CO 80303

Professor E. Brown
Dept. of Mech. Engineering
VPI and State University
Blacksburg, VA 24061

Dr. Edward W. Browning
Consumers Power Company
212 West Michigan Avenue
Jackson, MI 49201

Mr. T. Burgess
Fischer & Porter
County Line Roady
Warminster, PA 18947

Mr. E. E. Buxton
903 Hillcrest Drive
St. Albans, WV 25177

Mr. Philippe Ceylon
National Bureau of Standards
Bldg. 230
Washington, DC 20234

Prof. I. D. Chang
Dept. of Aeronautics
and Astronautics
Stanford Univ.
Palo Alto, CA 94305

Mr. M. J. Corbo
Exxon Research & Engineering Co.
180 Park Avenue
P. O. Box 101
Florham, NJ

Mr. Giles Crabtree
Singer/American Meter Co.
13500 Philmont Ave.
Philadelphia, PA 19116

Prof. C. T. Crowe
Dept of Mech. Eng.
Washington State Univ.
Pullman, WA 99164

Dr. R. W. Davis
National Bureau of Standards
Fluid Mechanics Bldg.
Washington, DC 20234

Mr. Nicholas Destefano
BIF Company
1600 Division Road
West Warwick, RI

Dr. H. H. Dijstelbergen
Ministry of Energy
Private Bag
Wellington
NEW ZEALAND

Mr. John Dobson
Foxboro Co.
38 Neponset Ave.
Foxboro, MA 02035

Prof. R. B. Dowdell
Univ. of Rhode Island
Dept. of Mech. Eng.
Kingston, RI 02881

Dr. William Durgin
Alden Research Laboratory
Worcester Polytechnic Inst.
Holden, MA 01520

Dr. Albert Ferron
Alden Research Laboratory
Worcestor Polytechnic Inst.
Holden, MA 01520

Dr. L. M. Fingerson
TSI Incorporated
500 Cardigan Road
P. O. Box 43394
St. Paul, Minnesota 55164

Mr. W. A. Fling
Cities Service Oil Co.
P. O. Box 300
Tulsa, OK 74102

Professor K. N. Ghia
Dept. Aero. Eng. & Applied Mech.
University of Cincinnati
Cincinnati, OH

Professor U. Ghia
Dept. Aero. Eng. & Applied Mech.
University of Cincinnati
Cincinnati, OH

Dr. Walter A. Goldstein
Bechtel Power Corp.
15470 Shady Grove road
Gaithersburg, MD

Dr. Philippe Grenier
Gaz de France - DETN
Alfortville
FRANCE

Professor K. R. Hall
Thermodynamics Research Center
Texas A&M University
College Station, TX 77843

Dr. A. T. J. Hayward
Moore, Barrett, & Redwood, Ltd.
107 Landor Road - Whitnash
Leamington, SPA
Warwick, CV3 12LF
UNITED KINGDOM

Dr. Patrick Hebrard
ONERA/CERT/DERMES
Toulouse
FRANCE

Dr. M. Hessel
National Bureau of Standards
Washington, DC 20234

Mr. J. A. Hicks
American Gas Association
1515 Wilson Blvd.
Arlington, VA 22209

Mr. H. Hillbrath
The Boeing Co.
UTC/CSD
P. O. Box 358 Boeing Trailer
Sunnyvale, CA 94086

Mr. T. Lee Hillburn
Phillips Petroleum Co.
112 TRW Building
Bartlesville, OK 74004

Mr. Jess Hord
National Bureau of Standards
325 S. Broadway
Boulder, CO 80303

Dr. E. H. Jones
Gulf R&D Co.
P. O. Drawer 2038
Pittsburgh, PA 15230

Mr. F. E. Jones
Building 230
National Bureau of Standards
Washington, D.C. 20234

Dr. Clarence Kemper
Kaye Inst., Inc.
15 De Angelo Dr.
Bedford, MA 01730

Dr. F. C. Kinghorn
National Engineering Lab
East Kilbride
Glasgow G750QU
Scotland, UNITED KINGDOM

Dr. Max Klein
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631

Professor C. Y. Kuo
Dept. Civil Engineering
VPI & State University
Blacksburg, VA 24061

Dr. J. A. Laurmann
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631

Dr. W. F. Z. Lee
Rockwell Int'l
400 N Lexington Ave
Pittsburgh, PA 15208

Mr. Mark Leitheiser
PPG Industries
10800 South 13th Street
Oak Creek, WI 53154

Gary Less
122 S. Michigan Ave.
Chicago, IL 60603

Prof. E. Lindgren
Engineering Sciences Dept.
Univeristy of Florida
Gainesville, GL 32611

Dr. Frank Little
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631

Dr. Oscar P. Manley, ER-15
Division of Engineering,
Mathematics & Geosciences
Department of Energy
Washington, D.C. 20545

Dr. G. E. Mattingly
Building 230
National Bureau of Standards
Washington, DC 20234

Mr. C. B. Mercer
Columbia Gas
P. O. Box 1273
Charleston, WV 25325

Mr. J. H. Messmer
Gulf R&D Co.
P. O. Drawer 2038
Pittsburgh, PA 15230

Mr. R. W. Miller
Foxboro Co.
38 Neponset AVe.
Foxboro, MA 02035

Mrs. E. F. Moore
National Bureau of Standards
Building 230
Washington, D.C. 20234

Prof. R. C. Mottram
Dept. of Mech. Engr.
University of Surrey
Guildford, Surrey GU25XH
UNITED KINGDOM

Prof. H. M. Nagib
Illinois Inst. of Tech.
Dept. MMAE
Chicago, IL 60616

Dr. Renny Norman
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 66031

Dr. Roger Norman
British Gas Corp. - Eng. Res. Station
Killingworth P. O. Box 1LH
Newcastle-on-Tyne NE 99 1LH
UNITED KINGDOM

Dr. R. Peters
Daniel Industries, Ltd.
Larbert Sterlingshire FK53NS
UNITED KINGDOM

Dr L. P. Purtell
National Bureau of Standards
Building 230
Washington, D.C. 20234

Dr. Sip R. Reintsema
NV Nederlandse Gasunie
Post Bus No. 19
9700 MA Groningen,
THE NETHERLANDS

Dr. Gregory Reynolds
National Bureau of Standards
Building 230
Washington, D.C. 20234

Dr. Baldwin Robertson
Building 230
National Bureau of Standards
Washington, D.C 20234

Mr. Erwin O. Rossbach
Brooklyn Union Gas Co.
195 Montague Street
Brooklyn, NY 11201

Prof. D. Sallet
Dept. of Mech. Engr.
Univ. of Maryland
College Park, MD 20742

Mr. L. Sarkas
American Gas Assoc.
1515 WIlson Bld.
Arlington, VA 22209

Mr. Toshio Satori
Yokogawa-Hokushin Electric Corp.
P.O. Box 4125 Shinjuku Ctr. Bldg. (50F)
25-1 Nishi-Shinjuku 1-Chome Shinjuku-Ku
Tokyo, 160 JAPAN

Mr. P. Scott
Foxboro
38 Neponset Avenue
Foxboro, MA 02035

Dr. Maurice Sevic
Dept. of the Navy
Naval Ship Res. & Dev. Center
Bethesda, MD 20014

Mr. W. Seidl
CEESI
P. O. Box 41
Nunn, CO 80648

Mr. C. Sindt
National Bureau of Standards
325 Broadway
Boulder, CO 80303

Dr. A. K. Singal
CHAM
P. O. Box 3367
Huntsville, Alabama 35810

Dr. E. A. Spencer, OBE.
National Engineering Lab.
East Kilbride, Glasgow G750QU
SCOTLAND, UNITED KINGDOM

Dr. C. Spiegelman
National Bureau of Standards
Administration Bldg. A337
Washington, D.C. 20234

Mr. David Spitzer
Nepera Chemical Co.
Route 17
Harriman, NY 10926

Mr. J. Stolz
Electricite de France
32 Rue de Monceau
75008 Paris FRANCE

Dr. D. A. Sullivan
FERN
536 MacArthur Blvd.
Bourne, MA 02532

Mr. Y. Z. Sun
Dept. of Mech. & Aero. Eng.
West Virginia University
Morgantown, WV 26506

Mr. Masaki Takamoto
Nat. REsearch Lab. of Metrology
1-4, 1-Chome Umezono
Sakura-Mura Niihari-Gun
Ibarati 305
JAPAN

Dr. R. G. Teyssandier
Daniel Industries, Inc.
P. O. Box 19097
Houston, TX 77024

Dr. C. Tilford
National Bureau of Standards
Washington, DC 20234

Mr. David Todd
Navy Primary Standards Lab
Naval Air Station-North Island
Code 066 Building 378
San Diego, CA 92135

Mr. H. A. Vega
Navy Metrology
Engineering Center
P. O. Box 2436
Pomona, CA 91769

Mr. Charles Waugh
Waugh Controls Corp.
9001 Fullbright Ave.
Chatsworth, CA 91311

Dr. Robert C. Weast
2 Bratenahl Place - Suite 4F
Bratenahl, OH 44180

Dr. James Whetstone
Building 230
National Bureau of Standards
Washington, D.C. 20234

Mr. M. L. Williams
Amoco Production Co.
P. O. Box 3092
Houston, TX 77001

Prof. M. Wilson
Dept. of Mech. Eng.
Univ. of Rhode Island
Kingston, RI 02881

Dr. J. Wong
Trans Canada PIpeline
P. O. Box 54
Commerce Court West
Toronto CANADA M5L1C2

Dr. T. T. Yeh
National Bureau of Standards
Building 230
Washington, D.C. 20234

Mr. Klaus Zanker
AGAR Corp.
2215 Bauer Drive
Houston, TX 77080

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